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CEEDO-TR-78-44

# Laboratory Evaluation of Expedient Pavement Repair Materials

Raymond S Rollings



JUNE 1978

FINAL REPORT FOR PERIOD JANUARY 1976-JUNE 1978



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CEEDO

CIVIL AND ENVIRONMENTAL
ENGINEERING DEVELOPMENT OFFICE
(AIR FORCE SYSTEMS COMMAND)
TYNDALL AIR FORCE BASE
FLORIDA 32403

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Past work and current technical literature were reviewed to determine potential capping materials for expedient repair of small craters (less than 20 x 20 feet repair areas) in airfield pavements. Seven materials identified in the literature review were tested in the laboratory to develop information on their strength and cure requirements. Accelerated high alumina cement, magnesium phosphate cement, three commercial asphalt products and unsurfaced, well compacted aggregate were recommended for field testing as the most promising small crater repair materials.

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PREFACE

This report was prepared by Detachment 1 (Civil and Environmental Engineering Development Office), Air Force Engineering&Services Center, Tyndall Air Force Base, Florida 32403 under job order number 21042B22. This report summarizes work done between January 1976 and June 1978. Captain Raymond S. Rollings was the project engineer.

Various commercial products are discussed in this report and are capitalized for identification. This report evaluates these products under very severe conditions for which they were not designed. No conclusions should be drawn about the performance of the products for normal applications and conditions as specified by the manufacturers.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS) where it will be available to the general public including foreign nations.

This technical report has been reviewed and is approved for publication.

Raymond S Rollings

RAYMOND S. ROLLINGS, Capt, USAF
Project Engineer

George D. Ballentine

GEORGE D. BALLENTINE, Lt Col, USAF
Asst Director of Civil Engrg Dev

JOSEPH S. PIZZUTO, Col, USAF, BSC
Commander

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## SECTION I

## INTRODUCTION

High performance military aircraft are dependent upon smooth, hard surfaced runways for both launch and recovery. This dependency is today one of the most vulnerable aspects of any military airfield. Widespread use of hardened aircraft shelters has reduced the vulnerability of individual aircraft, and attacks on the airfield pavement have become an effective method of reducing an opponent's air power. Improvements in weapon technology and accuracy in delivery and the development of small penetrating airfield attack munitions make it possible for a relatively small number of aircraft to interdict a runway and effectively prevent the opponents aircraft from participating in the conflict. Consequently, methods of rapidly repairing bomb damaged runways have become a vital aspect of insuring the survivability of airfields in forward areas.

Testing at Eglin AFB, Florida and Port Hueneme, California in 1963 and 1964 revealed that then existing repair techniques were inadequate for the gear loads and high tire pressure of modern tactical aircraft (References 1 and 2). This led to a series of tests at Eglin AFB, Florida in 1964 which examined a variety of possible repair techniques (Reference 3). From this work, the Air Force adopted its standard repair method of using debris from the bomb explosion to backfill the crater to within one foot of the surface, filling the last foot with a select fill, surfacing the repair with a patch of AM-2 landing mat and then anchoring the patch to the sound pavement around the crater. This repair technique was adopted by the Air Force in AFM 93-2 (Reference 4), but field testing of this repair technique at Tyndall AFB, Florida in 1973 revealed that some procedural modifications were required (Reference 5). A modified repair procedure was then adopted as AFR 93-2 (Reference 6) and field tested at Tyndall AFB, Florida in 1974. This test revealed that with some further modifications, trained personnel and properly maintained equipment, AFR 93-2 provided a marginal capability to meet the existing criteria of repairing three 750 pound bombs in four hours but was inadequate for repair of multiple small craters (Reference 7).

The Civil and Environmental Engineering Development Office (CEEDO) undertook a program to develop a small crater repair capability to supplement the existing AFR 93-2 capability. This program is limited in scope to currently available materials and procedures which will not require further research and development. This report will cover only the review of available materials and laboratory testing of selected materials. As potential repair materials were identified and tested, the US Army Waterways Experiment Station, Pavement Investigation

Division under contract to CEEDO conducted accelerated traffic tests of these materials in fabricated spalls (Reference 8). These tests were used with the results of the laboratory investigation to screen materials for further testing. Future studies will cover the field testing of various materials, and repair designs and the timed repair of actual blown craters.

Rapid repair of bomb damaged runways has been the subject of continuous research since 1963. Fairly comprehensive descriptions of the past research is available in References 5, 7, 9 and 10. In 1971 the Air Force Weapons Laboratory Civil Engineering Research Division became responsible for this research for the Air Force. In 1975 this responsibility was transferred to the Air Force Civil Engineering Center, Directorate of Engineering Materials, and in 1977 it was transferred to Det 1, AFESC (Civil and Environmental Engineering Development Office), Rapid Runway Repair Division, Tyndall AFB FL. Information on current research is available from this office.

## SECTION II

## CRITERIA FOR MATERIAL EVALUATION

The existing AFR 93-2 repair technique is oriented towards the repair of a few large craters (i.e. three 750 pound bomb craters in four hours) and is capable of handling the pavement removal, backfill and debris spoilage for small craters and camouflets such as shown in Figures 1 and 2. Capping materials are not currently available in the military for this type of damage or for spall damage. This section of the report discusses criteria for evaluating the acceptability of currently available materials for repair. These criteria include load capacity, material strength, cure time, cost, environmental conditions, shelf life and support equipment.

The loads and traffic for the repair area must be identified. Traditionally, emphasis has been on launch of tactical aircraft so cargo aircraft traffic has not been considered as a criterion for selecting materials. Table 1 shows several US built aircraft that might use repair strips in Europe and the Pacific. The amount of traffic from these aircraft that a repair must sustain has never been agreed upon. Early studies used the criterion of 16 passes (References 1, 3, and 13), but the tendency in more recent tests has been towards testing for 50 to 100 passes (References 7, 14 and 15). Discussions with research and planning agencies indicate that longer repair lives are highly desirable. This effort has assumed that the repairs must withstand at least 100 passes of traffic as a minimum acceptable capacity or 1400 passes (100 passes a day for two weeks) as a desired capacity.

The required strength of the capping material depends primarily on the applied load, number of repetitions of load, the thickness of the cap and the subgrade support. Table 2 shows California Bearing Ratio (CBR) values for various backfilled craters. A CBR of four appears to be a reasonable lower bound estimate of the subgrade support. Subgrade strength values might be lower if the ejecta used for backfill contains large quantities of highly plastic clay or plastic soils with high moisture contents.

Anderson in work with Fast-Fix cements (Reference 17) developed an empirical equation relating thickness, soil strength, load, tire pressure and material flexural strength as follows:

Figure 1. Small Crater, 25 Pound Charge, Tyndall AFB Field Tests (Reference 5)

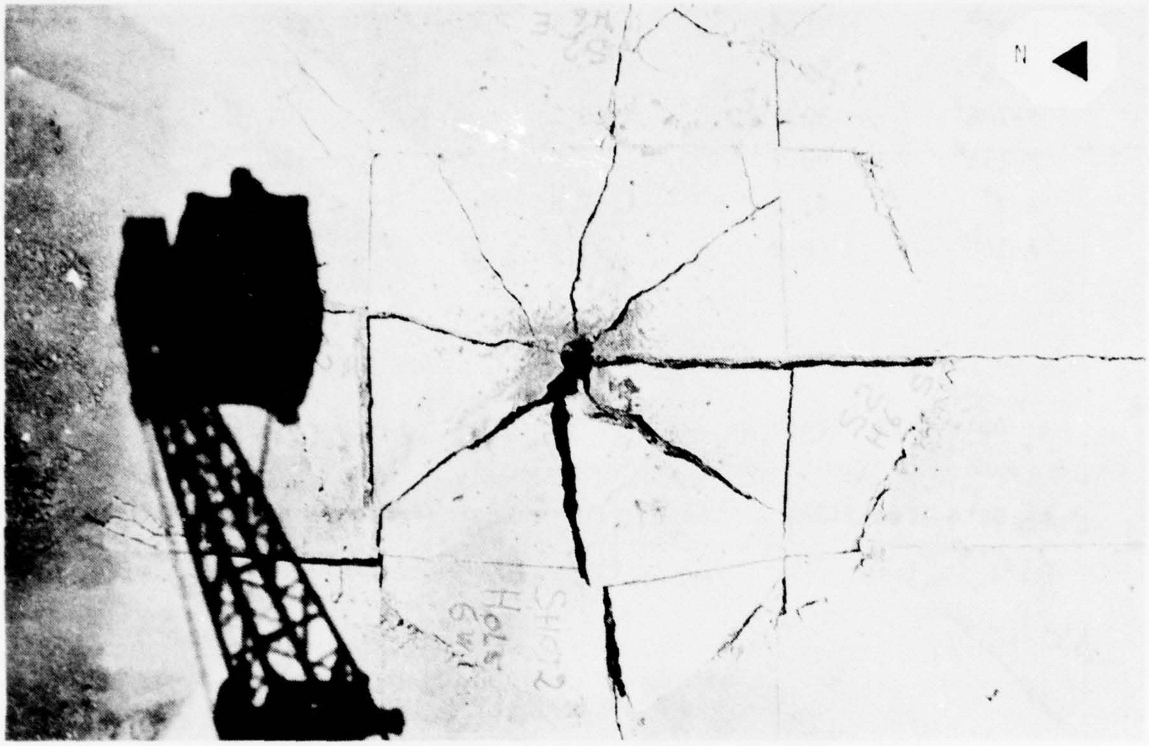


Figure 2. Camouflet, CERF Cratering
Studies (Reference 11)

TABLE 1. AIRCRAFT CHARACTERISTICS

| Aircraft | Maximum Takeoff Load (Kips) | Main Gear Load (Kips) | Tire Pressure (psi) | Contact Area ($in^2$) |
|---|---|---|---|---|
| F-4[a] | 61.7 | 27.0 | 265 | 102 |
| F-5[a] | 20.6 | 8.9 | 210 | 42 |
| F-15[b] | 51.0 | 23.4 | 260 | 90 |
| F-16[b] | 33.0 | 15.0 | 275 | 55 |
| F-106[a] | 39.6 | 18.1 | 285 | 63 |
| F-111[a] | 98.9 | 47.0 | 150 | 313 |
| A-7[a] | 42.0 | 17.5 | 280 | 62 |
| A-10[b] | 46.8 | 21.4 | 214 | 100 |

a Data from Reference 12.

b Data from files at the Air Force Engineering Technology Office.

TABLE 2. CRATER DEBRIS BACKFILLS

| Location | Soil[a] | Depth (in)[b] | CBR | Moisture (%) | Density (PCF) |
|---|---|---|---|---|---|
| 1. Ft Bragg 1962 (Reference 15) | | | | | |
| Test 1 | SP | 0 | 5 | - | - |
| Test 2 | SP | 0 | 4 | - | - |
| Test 3 | SP | 0 | 3 | - | - |
| 2. Eglin AFB 1963 (Reference 1) | | | | | |
| Test 3 | SP-SM | 6 | 4 | 1.0 | - |
| 3. Tyndall AFB 1973 (Reference 5) | | | | | |
| Test 1-2 | CL | 0 | 13 | 4.5 | 98.4 |
| 4. Tyndall AFB 1974 (Reference 7) | | | | | |
| Test 1 | SC | 0 | 7 | 9.7 | 127 |
| | SC | 16 | 6 | 8.9 | 134 |
| Test 2 | SC | 0 | 9 | 5.5 | 125 |
| | SC | 12 | 7 | 4.5 | 122 |
| Test 3C | GW[c] | 12 | 7 | 3.5 | 136 |

a Backfill soil type by Unified Soil Classification System.

b Depth below surface of backfill.

c Entire crater was backfilled with GW select fill. At the compacted surface, CBR was 31.

$$h = \frac{0.0028 \, L \, P^{.25}}{f^{.56} \, CBR^{.22}}$$

h = thickness of cap (inches)

L = wheel load (lbs)

P = tire pressure (psi)

f = flexural strength (psi)

CBR = California Bearing Ratio (dimensionless)

The tests to develop this equation used the failure criterion of 16 passes of an F-4 load without structural cracking in the capping material. This equation was found to be unsafe by Beal and Chandler (Reference 18), particularly for thin slabs (under four inches) and soft subgrades. Anderson's equation is based on supporting only a few repetitions of load and was used to select lower bounds for material strength. More conventional design methods were felt to be too conservative to establish the lower bound for the strength criteria. Final selection of repair materials and designs will have to be from the traffic testing which will follow this study.

Figure 3 shows the required pavement thickness for various flexural strengths for the aircraft in Table 1 as calculated by Anderson's equation with a subgrade CBR of 4. Curves are dashed when they fall below 4 inches because of the unsafe results of the equation in this range (Reference 18). For comparison with other design methods, a curve for the F-4 is also shown computed from the Corps of Engineers pavement evaluation curve for a modulus of subgrade reaction of 100 psi and 100 passes of the aircraft.

From these curves a 400 psi flexural strength was selected as the minimum desired flexural strength. This would require an 8 inch pavement for the F-4 and a 12 inch pavement for the F-111. A flexural strength of 600 psi was selected as a desirable strength since it would reduce the thickness to about 6 and 9½ inches for the F-4 and F-111. A 9½ inch pavement would also be adequate for the F-4 under the more conservative Corps of Engineers analysis. These strengths were selected as initial criteria and future field testing is required to evaluate their validity. Compressive strength is more commonly found in technical literature than flexural strength so approximations of the above flexural strength criteria were desirable. Using the following equation for portland cement concrete from Refererence 19:

$f = K (f_c)^{0.5}$
$f$ = flexural strength (psi)
$K$ = constant equal to 8-10
$f_c$ = compressive strength

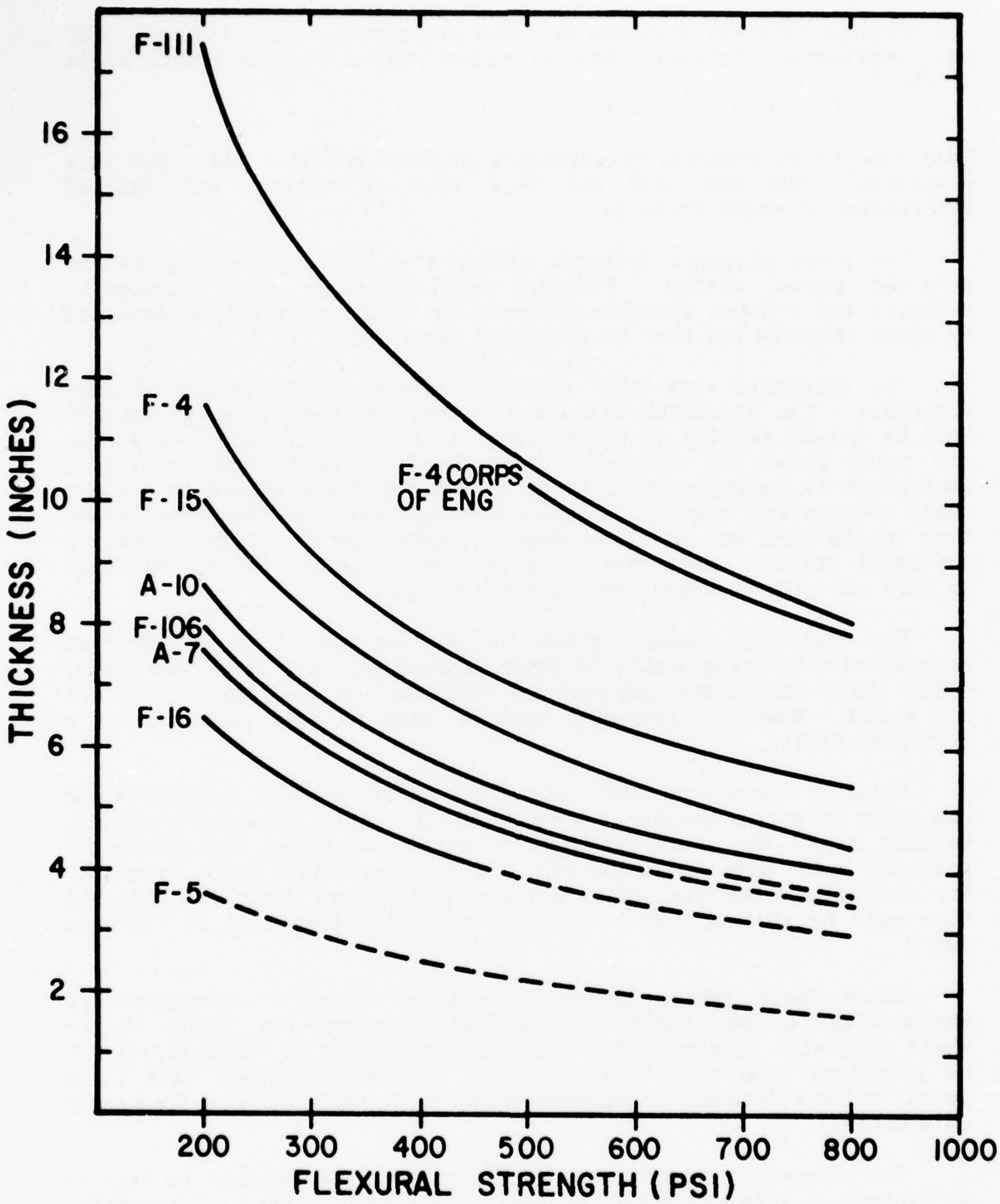


Figure 3. Pavement Thickness for Varying Flexural Strengths

the previous flexural strength criteria are approximately 1400 and 3600 psi compressive strength. Another approximation from Reference 20 is of the form:

$$f_c = -2123 + 10.02\ f$$

This results in compressive strengths of 1900 and 3900 psi. For this evaluation 1400 and 3600 psi were used as minimum and desired compressive strength criteria.

The above strength criteria assume that a structural cap is the selected repair method. Flexible repair methods using aggregate, asphalts and related flexible pavement material would not be governed by these criteria and must be evaluated separately.

The allowable cure time directly affects the strength of most materials. The strengths discussed in the preceeding two paragraphs must be gained rapidly if the material is to be of any use in allowing the rapid launch of aircraft. Test 3 of the 1974 BDR Field Test (Reference 7) indicates that 15 to 30 minutes are required to prepare small craters for capping. To be compatible with the four hour repair time in AFR 93-2 and to allow time for each team to repair several of the small craters, about two hours will be available for the material to cure and gain the required minimum strength.

The cost of a repair system for wartime must consider the cost associated with being unable to launch combat aircraft in an emergency. Under these conditions conventional construction cost guidelines are not valid. However, judgement must be used to keep costs within a practical limit.

Military operations must take place in all weather conditions and can occur in any geographical location in the world. Few materials can be used across the entire range of climatic conditions, and particular problems exist with obtaining rapid cure of materials below freezing. For this study the minimum acceptable temperature range for material cure will be 40°F to 100°F, and the desirable range will be -25°F to 125°F.

Since these repair materials must be stored in readiness for emergencies, a long shelf life is desirable, and the length of the shelf life will directly affect the long term cost of the material. To be practical high cost materials must have a long shelf life (five years) while relatively cheap materials can be replaced more frequently (six months).

The support equipment to be used with any material must be kept to a minimum. This includes storage equipment, mixers, dispensers, compactors, etc. Ideally the equipment should already be in the military inventory, or as a minimum it must be commercially available.

Table 3 summarizes the criteria which will be used to evaluate the potential of a material for rapid emergency repair of small craters and spalls in Air Force runways. Materials meeting these criteria are only a temporary interim solution and better long term solutions are still needed to reduce repair times.

TABLE 3. MATERIAL SELECTION CRITERIA

| Factor | Minimum Acceptable | Desirable |
|---|---|---|
| F-4 Traffic | 100 passes | 1400 passes |
| Flexural Strength[a] | 400 psi | 600 psi |
| Compressive Strength[a] | 1400 psi | 3600 psi |
| Cure Time | 2 hrs | Immediate |
| Cost | ---- | ---- |
| Environmental Conditions | 40°F-100°F | -25°F-125°F |
| Shelf Life | Varies with cost of material | |
| Support Equipment | Commercially Available | Military Inventory |

a Applicable only to rigid structural repair caps. Flexible repair concepts must be evaluated individually.

SECTION III

SELECTION OF MATERIALS

1. Introduction

Many of the past studies which considered materials for repair of weapon damaged runways were primarily concerned with repair of large bomb craters and the problems associated with material handling alone were sufficient to remove many materials from consideration. By restricting use of materials to small craters (roughly 20 feet by 20 feet or less) and spalls, some of the materials eliminated in these earlier studies show promise of meeting the limited criteria developed in Section II. Also industry has done a considerable amount of work on materials for rapid repairs to urban freeways and bridge decks which may be applicable. Hydraulic cements, bituminous materials, polymers, and miscellaneous materials will be considered separately to identify materials which might meet the specifications of Section II.

2. Hydraulic Cements

a. Portland Cement

There are five basic types of portland cement available on the market today: Type I, common cement; Type II, modified cement; Type III, high early strength cement; Type IV, low heat cement; and Type V, sulfate resistant cement. The relatively slow rate of cement hydration of conventional portland cement immediately limits their use. Type III high early strength cement gains rapid high strength due to finer grinding and larger proportions of $C_3A$ than other types of cement. Table 4 shows typical chemical composition of Types I and III portland cements. Strength gain in high early strength concretes is still not adequate. Pike and Baker in Reference 22 report compressive strengths of only 300 psi at 8 hours and of 2800 psi in 24 hours. This is far short of the 1400 psi in two hours that is needed. Calcium chloride ($CaCl_2$) has been found to be an effective accelerator and is believed to act as a catalyst in the hydration of $C_3S$ and $C_2S$. Neville in Reference 23 reports that Type III cement compressive strengths can be increased by 1000 psi at 24 hours by addition of CaCl2 while Reference 24 reports addition of 2 percent $CaCl_2$ to Type III cement gave strengths of approximately 350 psi at 8 hours, 2400 psi at 16 hours and 3350 psi at 24 hours. Bussone, Bottomley and Hoff in Reference 25 report strengths as high as 1200 psi at 2 hours with Type I cement with a sodium metasilicate accelerator. Results were variable and the mixes were sensitive to the proportioning of the accelerator.

## TABLE 4. TYPICAL COMPOSITION OF TYPES I AND III PORTLAND CEMENT

| | Portland Cements | |
|---|---|---|
| | Type I[a] | Type III[a] |
| $C_3S$[b] | 49 percent | 55 percent |
| $C_2S$[c] | 26 | 14 |
| $C_3A$[d] | 11 | 10 |
| $C_4AF$[e] | 8 | 7 |
| Mg O | 3.0 | 2.1 |
| SO3 | 2.2 | 2.8 |
| Free CaO | 1.0 | 1.6 |
| Ignition Loss | 1.3 | 1.5 |

a Reference 21

b Tricalcium silicate, $3\ CaO \cdot SiO_2$.

c Dicalcium silicate, $2\ CaO \cdot SiO_2$.

d Tricalcium aluminate, $3\ CaO \cdot Al_2O_3$.

e Tetracalcium aluminoferrite, $4\ CaO \cdot Al_2O_3 \cdot Fe_2O_3$

Increases in surface area of individual cement particles by finer grinding will result in more rapid strength gains. Bennet and Collins in Reference 26 report strengths of 3350 psi at 8 hours for a special cement with specific surface of 7420 $cm^2/g$ while Neville in Reference 23 reports that ultra high early strength portland cement marketed in Great Britain with a fineness of 7000 to 9000 $cm^2/g$ develops a strength of 1800 psi in 8 hours. A variety of accelerators for portland cement are marketed today, many of which are proprietary products. Reference 9 has an extensive review and bibliography on this subject.

Because of the variety of references involved no attempt has been made to try to separate factors such as water cement ratio, mix design or test method which have strong effects on the strength of concrete. With the possible exceptions of very finely ground cement or the use of sodium metasilicate accelerator, portland cement does not appear to have the required strength gain.

The widespread availability of portland cement and its required equipment and the relative low cost of materials are all definite advantages. However, placing portland cements under adverse environmental conditions poses serious problems. At high temperatures (above 75°F) strength decreases and special care must be taken to insure proper cure. At freezing or near freezing temperature, hydration is slowed and the newly placed concrete must be protected against freezing by use of accelerators, heating and insulation (Reference 19).

b. Regulated Set Cement

Regulated set cement was developed and patented by the Portland Cement Association and is manufactured and marketed under licenses granted by Portland Cement Association. Licenses have been granted to a number of manufacturers in the U.S., Asia and Europe, but only one manufacturer in Germany is known to be currently producing the product.

This cement contains from 1 to 30 percent calcium haloaluminate which accounts for its rapid strength gain. Generally the halogen in the haloaluminate is fluorine. The set time can vary from 1 to 30 minutes depending on the manufacturer of the cement and often citric acid is used as a retarder. Reference 27 contains a summary of the effects of varying chemical composition and of the variation in strength gain of regulated set cements from different manufacturers.

Reported strength gain for regulated set cements varies considerably between different sources. Bussone, Buttomley and Hoff in Reference 25 report strengths at 2 hours of 1100 psi and with a sodium metasilicate accelerator this increased to 4100 psi. Pike and Baker in Reference 22 report a two hour strength of only 360 psi. Dr Ledbetter

of Texas A and M University stated in private communication that he had obtained strengths of 800 psi at four hours. Hokanson in Reference 5 reports that cores recovered from a regulated set concrete test section had strengths varying from 1090 to 1480 psi after 18 days. Collum. Denson and Hoff report 3 hour compressive strengths of 700 to 865 psi and 3 hour flexual strengths of 165 psi (References 28). These variations in reported strengths illustrate the difficulty of obtaining regulated set cements with consistent performance. This is felt to be due to the lack of an accepted specification for the material.

Since 1971 regulated set cement has been closely examined for possible application in repair of bomb damaged runways (References 5, 25, 27, and 28). A series of tests of regulated set cement was included in the 1973 field test at Tyndall AFB, Florida (Reference 5). In test 1-4 NW the crater from a 25 pound charge was filled with foamed regulated set cement and then the final foot was filled with a neat regulated set cement slurry. A 48 kip load on a 12 inch diameter plate resulted in a punching shear failure of the cap after a 90 minute cure. Within a few weeks the repair was destroyed by thermal expansion and cracking. Test 1-4 SW poured a neat 12 inch cap of regulated set slurry over well compacted debris backfill. A 48 kip load on a 12 inch diameter plate resulted in a .16 inch penetration of the plate into the cap. Test 1-4 SE percolated a regulated set slurry into a preplaced aggregate cap over a moderately compacted debris backfill. The 48 kip load caused a 0.10 inch penetration of the cap on the crater surface. Test 2-1 was the repair of a 750 pound bomb crater along the same lines of test 1-4 NW except plastic pipe modules were stacked in the crater to reduce the quantity of cement needed. The repair was unable to support load due to thermal damage to the modules, and the repair suffered thermal expansion and cracking identical to that of Test 1-4 NW. A second series of tests was attempted along the lines of Test 1-4 SE because of its apparent success, but the regulated set cement failed to gain strength and further testing of regulated set cement was discontinued by the Air Force.

The US Army Corps of Engineers has continued work with regulated set cement for possible permanent repair of bomb damaged airfield pavements. The 293d Engineer Batallion at Baumholder, Germany conducted a series of trials with regulated set cement which culminated in a demonstration repair on 6 April 1977 (Reference 28). The repair team successfully repaired a 750 pound bomb crater in 4 hours using 34 personnel. The crater was backfilled with debris, 18 inches of aggregate was placed and compacted and then the repair was capped with 12 inches of regulated set cement. The concrete was mixed in transit mix trucks and dispersed directly from the trucks around the edge of the crater and from a large concrete pump for the interior portions of the repair. No method was available for load testing the repair. The Waterways Experiment Station continued this investigation and carried

out accelerated traffic tests for several regulated set concrete repairs during August of 1977. The regulated set cement used for the tests by the Waterways Experiment Station was inferior to that used in Germany and strength gain was slow. A technical report describing these trafficking tests with regulated set cement is being prepared by the Waterways Experiment Station.

Houston and Hoff (Reference 30) found that regulated set cement has considerable potential for cold weather concreting. Like conventional portland cement, regulated set cements must be protected against freezing until they gain some minimal strength. However, the accelerated cure of regulated set cement shortens the time that the cement must be protected and heated, and the cement's higher exotherm helps maintain higher cure temperatures in cold environments. Specimens protected against 15°F temperatures for 1 to 24 hours required two to three days to exceed 1400 psi compressive strength.

c. High Alumina Cements

The raw materials for high alumina cements are limestone or chalk and bauxite resulting in a final cement of about 40 percent each of alumina and lime with some ferrous and ferric oxides and up to 8 percent silica. The main cementitious compounds are the calcium aluminates CA and $C_5A_3$ with the hydration of CA providing the highest strength gain (Reference 23). High alumina cements are marketed under a variety of trade names. Some of these are: Ciment Fondu, Lightning (Great Britain), Fondu, Lumnite (United States), Fondu Lafarge (France), Rolandshutte (Germany), Istrabrand (Yugoslavia), Citadur (Hungary and Czechoslovakia), Fundido Electraland (Spain), Alcement Lafarge (Scandinavia), and Ashai Foundu (Japan).

High alumina cements gain about 80 percent of their ultimate strength in 24 hours, but this rapid strength gain is not accompanied by rapid setting. British Standard 915: 1947 requires the initial set to occur between two and six hours after mixing and final set within two hours of the initial set (Reference 23). When the cement is exposed to hot, moist conditions a loss of strength takes place due to the conversion of the hexagonal aluminate hydrates $CA\,H_{10}$ and $C_2AH_8$ to the more stable cubic hydrate $C_3AH_6$. The specific gravity of $CAH_{10}$ is 1.72 and the specific gravity of $C_3AH_6$ is 2.52 so that the conversion results in increased porosity and decreased strength. Figure 4 shows the effects of temperature on samples of high alumina mortar with a water cement ratio of 0.65 cured in water. Strength is expressed as a percent of the strength obtained by samples at room temperature, which was 7400 psi at 3 days and 8200 psi at 14 days (Reference 30). Table 5 shows the long term loss of strength of high alumina cement (Reference 31). For these reasons the British Code of Practice for the Structural Use of Concrete, CP110:1972, requires high alumina cement to obtain higher 24 hour strengths than 28 day strength for portland cement and limits the water cement ratio to 0.40 or less.

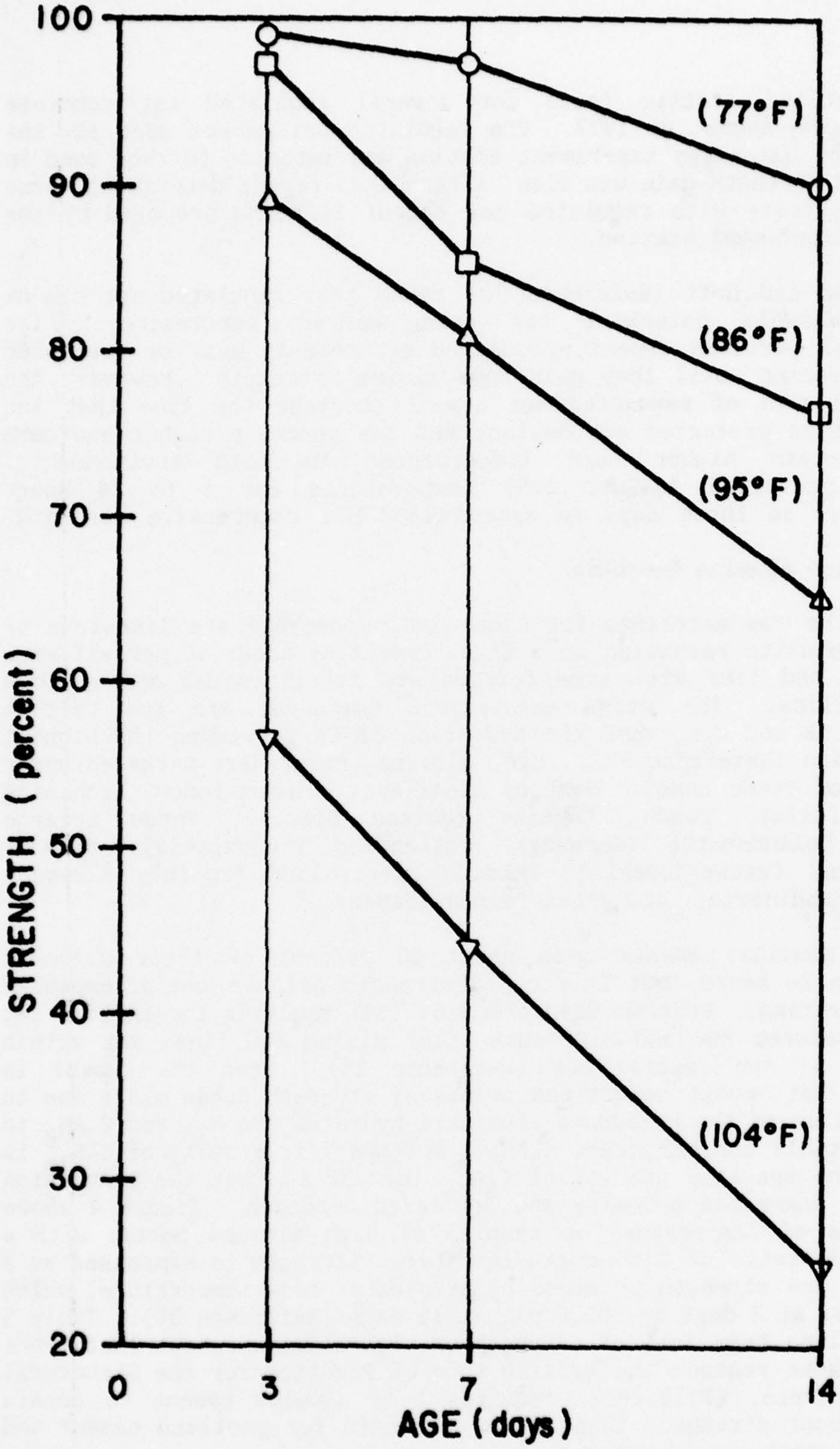


Figure 4. Temperature Effects on High Alumina Cement (Reference 30)

TABLE 5. LONG TERM STRENGTH LOSS OF HIGH ALUMINA CEMENT
(Reference 31)

| Storage | W.C. Ratio | Strength at 21 Years (psi) | 21 Year Strength as A Percent of Maximum[a] |
|---|---|---|---|
| Laboratory | 0.40 | 5500 | 55 percent |
| | 0.64 | 3870 | 41 percent |
| Outdoor | 0.40 | 2880 | 31 percent |
| | 0.60 | 1920 | 23 percent |

a Maximum generally at one year of age.

High alumina cements do not gain strength rapidly enough in the first few hours to be usable for rapid runway repair without some accelerator. Mr Netter of Lonestar Lafarge Company reports in a private communication that addition of 0.1 percent lithium carbonate to high alumina cement has given compressive strengths of 1850 psi in one hour and 3000 psi in two hours.

Mixes of portland cement and high alumina cement set and also gain strength rapidly but the ultimate strength is lowered. Bussone, Bottomly and Hoff in Reference 25 were unable to get good results with mixtures of high alumina cement and portland cement, but References 9 and 23 indicate others have had success with this technique. High alumina cement from different sources can be expected to react differently with admixtures such as lithium carbonate or portland cement.

Fondu's rapid strength gain may also give it cold weather repair characteristics similar to regulated set cements. It has demonstrated the ability to bond well to conventional portland cement concrete (References 32 and 34).

d. Gypsum Cements

A variety of gypsum cements are available for various industrial uses. These cements are generally alpha crystal gypsum (gypsum semihydrate, $CaSO_4 \cdot 1/2\ H_2O$) differing primarily in grain shape, density and additives. When mixed with water, these materials harden and gain high strength rapidly.

Gypsum base cements were studied extensively by the Air Force for use in repair of bomb craters from 1967 through 1971. Setser et al (Reference 13) tried a variety of different combinations of materials before settling on combinations of gypsum and portland cement as the most promising fast setting material available. This work developed Fast-Fix I (95% hydrostone gypsum and 5% portland cement and the less costly Fast-Fix 2 (80-95% IP gypsum and 20-25% portland cement). Fast-Fix I was the preferred product for repair of bomb damaged airfields. This product could obtain 30 minute compressive strengths of 3500 psi and flexural strengths of 600 psi. Set time was around 12 minutes. A follow-on effort by Pruitt et al (Reference 34) developed mixing and dispensing equipment and successfully demonstrated repair of craters at Eglin AFB, Florida. Other variations of FastFix with hydrocal white gypsum cement were known as Fast-Fix 3, Fast-Fix C1 and Fast-Fix $C_2$.

Enemy attacks on airbases in South Vietnam resulted in an expedited study by Anderson and Ames (Reference 17) to examine use of Fast -Fix for repair of rocket and mortar damaged runways. They developed Fast-Fix 3 mix designs and demonstrated that Fast-Fix concretes could be prepared in conventional transit mix trucks.

Several other investigators have examined various mix designs and uses of Fast-Fix cements (References 35, 36 and 37). Zwolinski (Reference 38) constructed and observed three patches of Fast Fix at Elmendorf AFB, Alaska. Lehman, Koch and Wenk (Reference 39) reported that the set time of hydrostone gypsum cement stored in paper bags increased from 15 minutes to 45 minutes after one month storage at 90°F and 90 percent relative humidity; when stored in sealed rubber bulk containers, the set time increased to 30 minutes after four months of storage.

In 1968, a number of Air Force field engineering organizations in Korea, Vietnam, Germany and the US tried Fast Fix cements in field evaluations. These repairs were primarily small spalls or chuck holes, and the materials were mixed both by hand and by mechanical mixers. Where quality control was good and mixing directions were carefully followed, results were satisfactory. There were a few instances of rapid wear under traffic.

From 1969 to 1970 the Waterways Experiment Station carried out laboratory and field tests of Fast-Fix 1 and Fast-Fix C-1. This work was primarily oriented toward developing information on material properties and examining reinforcement for Fast Fix concrete. Nylon fibers, fiberglass strands, fiberglass fabric, steel fiber wire, steel grid reinforcing and several proprietary additives were tested. Only the conventional steel grid reinforcing proved successful, and a 4 inch thick slab of Fast-Fix with double layers of steel grid reinforcing over a 3 CBR subgrade withstood 50 passes of an F-4. Proper design of load transfer at repair edges was found to be critical, and several methods of load transfer were investigated. Thickened edges and placement of landing mat under the edge of the Fast Fix slab were found to be satisfactory.[a]

Fast-Fix cements have proven capable of rapidly obtaining high strength at temperatures down to 45°F (Figure 5), but the Air Force has not adopted Fast-Fix as a standard repair material because of difficulty in storing and handling the material and very poor durability of repairs. The increase of set times reported by Koch and Wenk in Reference 30 indicates that long term storage of hydrostone gypsum cements will be difficult. The field evaluation of Fast-Fix cements by Air Force field engineering organizations gave mixed results depending on local quality control. Beal and Chandler (Reference 18) identified five limitations of gypsum cement:

1. Set time affected by mixing energy.
2. Set time affected by water cement ratio.
3. Auto-acceleration of gypsum by gypsum hydration products.

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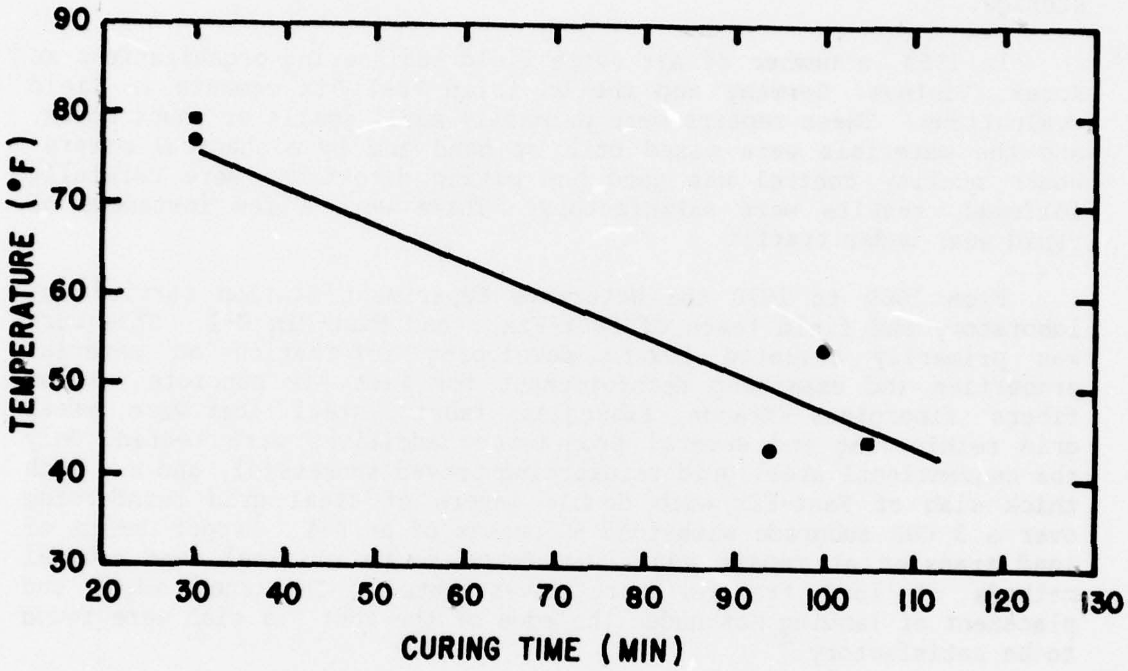
[a] No technical report was published on this work. Data and a copy of a draft report by Mr Abbot was provided courtesy of Mr A. H. Joseph, Waterways Experiment Station, Pavement Investigation Division.




FLEXURAL STRENGTH - 500 PSI

WATER CONTENT - 30% BY DRY WEIGHT

MIXING TIME - 3 MIN

Figure 5. Temperature Effect on Fast-Fix Cure Time (WES Data)

4. Absorbed moisture affects set time and strength.
5. Variations due to manufacturing process.

As an example of one of these effects, Figure 6 from Reference 18 illustrates mixing speed and mixing time on set times. None of the problems alone preclude use of Fast-Fix cements, but the combination of all factors make it very difficult to use Fast-Fix as a standard AF repair material.

Beal and Chandler (Reference 18) in 1971 conducted the last Air Force Fast-Fix study. This study concluded that either Fast-Fix 1 or 3 could be used for emergency repair, but because of poor durability, Fast-Fix repairs must be considered only as temporary, expedient patches and should be replaced as soon as possible. Also, because of their excessive creep under load, Fast-Fix cements should not be used for structures where dead loads provide a major portion of the load.

Probably the major objection to Fast-Fix cement has been its reported poor durability. Zwolinski (Reference 38) reported that patches subjected to light traffic began showing deterioration in about three months and a patch subjected to heavy vehicular traffic began cracking in one month, spalling in four months, and after one year the patch was severely deteriorated. Rapid deterioration was also reported by some Air Force organizations participating in the field evaluations of the material. Table 6 shows the strength loss of 7 day old Fast-Fix concrete due to exposures to freezing and thawing. In comparison, normal portland cement concrete can withstand 500 cycles of freezing and thawing. Although cycles of freeze-thaw cannot be related directly to expected field conditions, they do indicate a severe durability problem with Fast-Fix.

Several other gypsum cements are commercially available. Duracal is a product of US Gypsum Company consisting of gypsum and portland cement. Compressive strengths reported for this material range from 700 psi at 2 hours (Reference 22) to 2000 psi at 1 hour (Reference 40). Maricrete, a product of Atlas Minerals and Chemical Division, ESB Inc, is another mixture of gypsum and portland cement with 8 hour strengths reported to be 500 psi (Reference 40).

e. Very High Early (VHE) Cement

The US Gypsum Company has developed and plans to market a new fast setting cement known as Very High Early (VHE) cement. This material consists of essentially anhydrous hydraulic calcium silicates and calcium sulfoaluminate. Dr Ledbetter, in a private communication, reports obtaining VHE concrete compressive strengths ranging from 3260 to 4750 psi at four hours. No other data on this material is available.

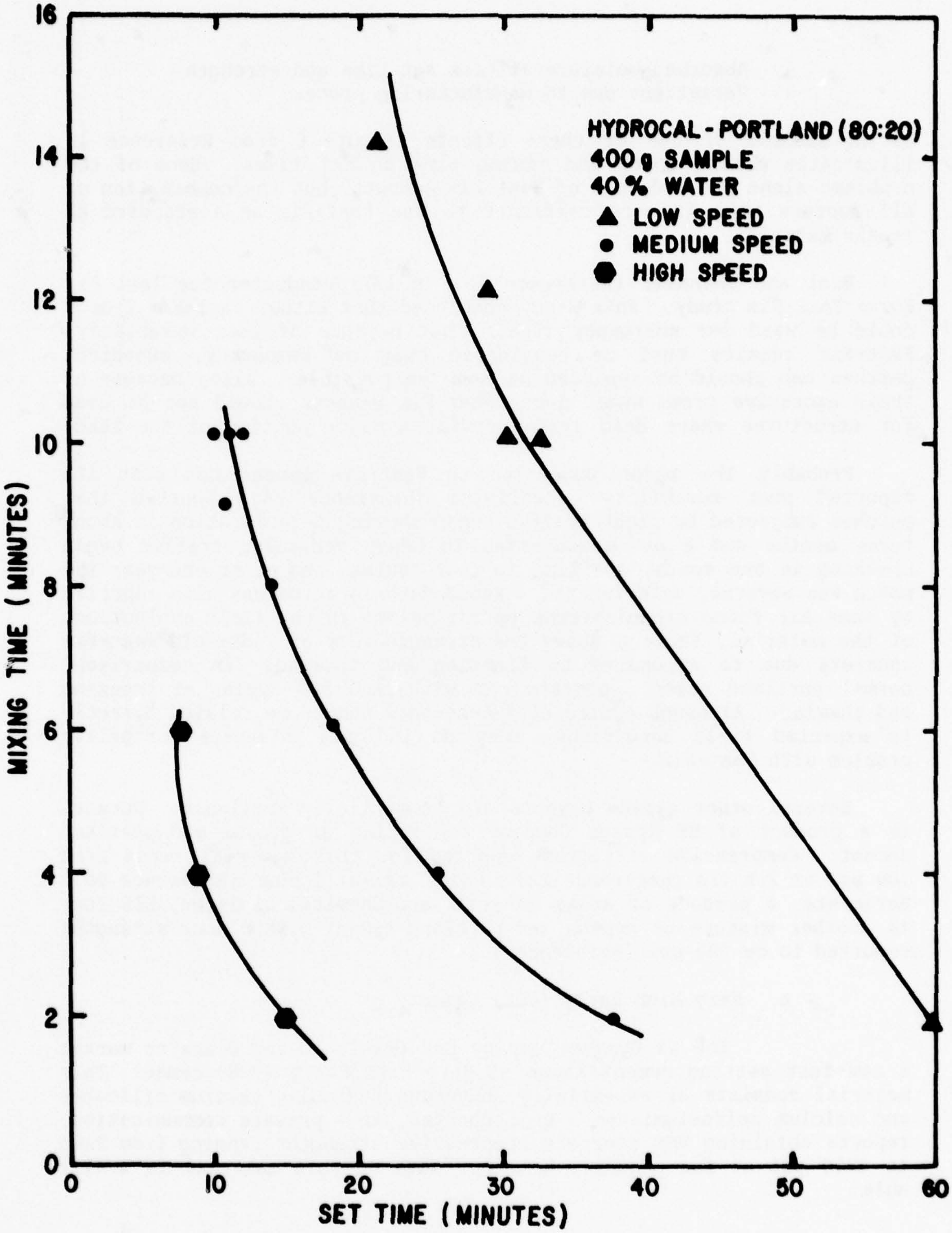



Figure 6. Effect of Mixing Energy on Fast-Fix Set Time (Reference 18)

TABLE 6. RESULTS OF FREEZE-THAW ON FAST-FIX CONCRETE

(REFERENCE 18)

| Formulation | 50 Cycles Flexural Strength (psi) | 50 Cycles Compressive Strength (psi) | 100 Cycles Flexural Strength (psi) | 100 Cycles Compressive Strength (psi) |
|---|---|---|---|---|
| FF1 | 8 | 2325 | 0 | 0 |
| FF3 | 123 | 2119 | 0 | 0 |

NOTE: In general flexural strength loss is considered as a good indication of freeze-thaw resistance and compressive strength is considered as a poor indicator (Reference 21).

f. Miscellaneous Cementatious Products

A large variety of commercial products for pavement repair are on the market today. These will not be discussed in detail due to advertised data that does not meet the criteria of Section II, poor performance in past tests or lack of information. Among the commercial products available are: Por Roc from Hallemite Corporation (References 3, 13 and 41), Mirament from Seddon Company (References 13, 40, and 42). Speed-Crete from CMP, Inc (References 13 and 41), Siroc from Diamond Alkali Co (Reference 3), Pre-Krete from Pocono Fabricators (References 41 and 42), Five Star Highway Patch from Construction Products Research, Inc. (Reference 22), Prepatch from Ransom and Randolph Company (Reference 22), Silico Phosphate Cement from Monsanto Corporation (References 22 and 43) and Fix-A-Crete from Custom Building Products (Reference 40).

3. Bituminous Materials

a. Load Carrying Capacity

Flexible pavements consist of a relatively thin bituminous wearing course underlain by varying thicknesses of a base course and subbase which protect the subgrade from overstressing. These underlying layers of material are generally granular soils which may be stabilized or unstablized. Any bituminous material used for rapid repair of an airfield runway must have a properly constructed supporting base course as an integral part of the repair design.

b. Hot Asphalt Mixes

Field tests at Port Hueneme, California (Reference 2) used hot, plant mixed, asphalt concrete for the repair of several craters from 250 and 500 pound bombs. Craters were backfilled with compacted sandy gravel and then surfaced with a 3-inch depth of hot asphalt concrete. Samples from the asphalt surface had an average Marshall stability of 1820, flow of 16 and a unit weight of 139.2 $lbs/ft^3$. The aggregate gradation did not meet Corps of Engineer specifications for airfield pavements for high pressure tires (Reference 44). The repairs were structurally adequate to support 30 passes of an F-4B (27000 pound load, 400 psi tire pressure) after the asphalt had cooled. Attempts to traffic the asphalt while it was still warm were unsuccessful. Reference 2 estimates that construction of 250 pound and 500 pound crater repairs with hot mix asphalt would require 5 to 7 hours and 6 to 8 hours respectively. Another estimated 6 hours would be required for the asphalt to cool before traffic could begin. This requirement for cooling is open to debate. A properly designed lean mix meeting gradation requirement for high pressure tires (Reference 44) may be able to support traffic with appreciably less or even no cooling.

The Waterways Experiment Station attempted 2 and 5 foot diameter spall repairs using a simplified macadam type construction and hot penetration grade asphalt cement (Reference 8). This repair was unstable under F-4C traffic (25000 pound load, 250 psi tire pressure). Improved gradations and construction techniques would improve performance under traffic but would require longer construction times.

A major drawback to using hot asphalt in any form is the requirement for extensive heating equipment. At least one model of a small, mobile truck mounted asphalt plant is commercially available from National Asphalt Machinery Company, but heating time for the asphalt would still be a drawback. Until some practical method of rapidly heating sizable quantities of asphalt cement is developed, hot asphalt repairs do not appear practical for rapid repair of damaged airfields. It remains a promising material for permanent repairs.

c. Liquid Asphalts

A liquid asphalt can be made by cutting an asphalt cement with a solvent such as gasoline or naptha (Rapid Curing (RC) cutbacks), kerosene (Medium Curing (MC) cutbacks) or fuel oil (Slow Curing (SC) cutbacks). A second approach is to disperse particles of asphalt cement in water with various emulsifying agents. These liquid asphalts can then be used in place of hot asphalt but the stability of these mixes depends on the evaporation of the solvents in cutback asphalts or of the water in an emulsified asphalt. Asphalt concrete mixes made in this manner are generally known as cold mix and may be used immediately for RC cutbacks and rapid setting emulsified asphalts or stockpiled for future use if made from MC and SC cutbacks or slow setting emulsified asphalts.

The 1963 field tests at Eglin AFB (Reference 1) used conventional cold mix and cold mix reinforced with perforated steel planking as surfacing for several crater repairs but the repairs performed poorly under traffic. The properties of the cold mix were not reported; base course materials were of poor quality; and construction was poor. These facts make it impossible to evaluate the cold mix asphalt's performance.

The Waterways Experiment Station tried several different cold mix asphalt repairs on 2 and 5 foot diameter holes, but the cold mix rutted and raveled badly under traffic (Reference 8). Conventional stockpiled cold mix does not have sufficient stability to be used in rapid airfield repairs.

Liquid asphalts can be mixed with aggregate directly at the work site by means of travel mixers, graders or drags. Aggregate is placed in windrows; asphalt is added; and then the two are mixed and aerated in place before final placing and compaction. The time requirements to mix and aerate the road mix are excessive for this study and the speed of curing is highly dependent on the weather (Reference 45).

Another repair method at the crater site would be macadam construction. In this procedure large open graded aggregate is placed and rolled, and then asphalt cement is applied. A finer aggregate is then placed and rolled. Depending on anticipated traffic and desired quality of pavement, the application of aggregate and asphalt is continued to the desired thickness and surface quality. At the Eglin AFB field tests in 1965 (Reference 3), two repairs were attempted using alternating layers of four inch and 3/4 inch graded aggregate. RS3K emulsified asphalt and RC4 (RC800 under new liquid asphalt grading system) cutback asphalt were applied at a rate of 0.2 gallons/yd$^2$. The RS3K remained tacky for several hours and could not be tested. The RC-4 was trafficked within 15 minutes of application, and the rut depth increased from 3/8 inch on the initial pass to one inch on the fourth pass of a 29 kip load. Under the hot and dry weather conditions RC-4 was felt to be an acceptable temporary surfacing, but this limitation is too stringent for this study.

Emulsified asphalt technology has improved greatly in recent years and may eventually develop to a point where it is usable for rapid crater repair. However, curing times are too long; long term storage can be a problem and there have been reports that some aggregates have proven to be temperature sensitive when mixed with emulsified asphalts (Reference 47) which further limits its applications. Cutback asphalts have the same problem with curing time as emulsified asphalts.

c. Asphalt and Sulfur Mixtures

Sulfur has been successfully combined with asphalt and low grade aggregate to make high quality paving mixtures (Reference 45) and has also been used alone to make a strong concrete (Reference 46). However, these mixtures still require heating to 245°F – 305°F. The requirements for heating and cooling this material prevent it from being considered within the criteria for this study.

e. Commercial Asphalt Materials

A number of asphalt base repair materials are marketed as patching compounds. The following six products are felt to be representative of the general types of available commercial asphalt products.

Amicrete, a patented, dense-graded asphaltic cold mix manufactured by Southern Amestite, was tested at Eglin AFB in 1965 (Reference 3). Four passes of a 27 kip wheel load formed ruts two to four inches deep. This material proved unsuitable for patches subjected to F-4 loads and tire pressure.

The US Navy developed and tested a premixed hot asphalt paving mixture for small scale patching jobs. An emulsified asphalt was premixed with fine aggregate and bagged for storage. At the work site,

the bagged emulsified asphalt and fine aggregate were mixed with coarse aggregate, heated until the water in the emulsion was driven off and then the hot mixture was applied. A Littleford Model 700 heater-mixer was capable of heating seven cubic feet of the patching material for application in six minutes. Laboratory and field results were both satisfactory, and the material was recommended for field use (Reference 49). This material is not in commercial production.

Zor-X is an emulsified asphalt, liquid coal tar and aggregate mixture marketed by the Monroe Company. Zor-X is applied and compacted cold and is capable of taking traffic as soon as compaction is completed. This material is stored in 55 gallon drums and, when left sealed, has an indefinite shelf life. Several AF bases have successfully used Zor-X for patching areas up to 4 ft x 20 ft x 4 inches deep. Some of these patches are up to ten years old. These patches have been put down under a wide variety of climatic conditions and have been subjected to different types of aircraft and vehicular loads.[b] During tests at the Waterways Experiment Station Zor-X rutted under F-4 traffic but did not break up or ravel (Reference 8). Cost for this material is high.

Amalgapave, formerly marketed as Super Cold Mix, is a patented patching material marketed by Bray Oil Company. A dense-graded aggregate is mixed with a Bray Oil developed hardener, Diazite, and then cutback asphalt is added and mixed. The finished product is known under the trade name of Amalgapave. The hardener provides initial stability and progressive hardening of the asphalt binder after the material has been compacted. About 20 pounds of Diazite are required per ton of mix. Diazite's current cost is about 16¢ per pound. Amalgapave can be stockpiled for about one year, and repairs can be opened to traffic immediately after compaction. This material has been used successfully for patching at Los Angeles International Airport and is reportedly unaffected by the presence of moisture. Patches have withstood heavy commercial aircraft traffic without any sign of ravelling or rutting.[c] Several mixes of Amalgapave were subjected to F-4 traffic at WES without severe distress (Reference 8).

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[b] Information provided by base civil engineering squadrons at Korat AFB, March AFB and Altus AFB.

[c] Private communication with Mr Arvid Cook, City of Los Angeles Department of Airports and personal inspection by author.

Future Patch is a proprietary cold mix asphalt marketed by 21st Century and Construction Materials Corporation. The product is provided in several different grades for different environmental conditions. The product is packaged and handled similar to ZOR-X but only costs about half as much. Its performance in 2 and 5 foot diameter spall repairs at WES was comparable to Amalgapave (Reference 8).

The Kentucky Department of Transportation has had good success with Sylvax, Unique Paving Material (UPM) as an improved patching material over conventional cold mix. During the 1976-1977 seasons they used 5000 tons of the material for road maintenance. Use of the material is restricted to small confined chuckholes on high traffic volume highways, on wet, cold surfaces or other emergency patching where weather is a problem (Reference 50). A year long study was conducted of 318 pothole repairs at 26 municipalities around the country. Approximately one-third of these repairs used conventional cold mix and the remainder used Sylvax UPM. The Sylvax UPM patches showed a three fold increase in the percentage of successful patches, an improved weather tolerance and an improved capability to repair larger chuck holes when compared to conventional cold mix (Reference 51). Sylvax UPM repairs of 2 and 5 foot diameter spalls rutted and broke up under simulated F-4C traffic during testing at WES (Reference 8). Although the material is reportedly adequate for road patching, it is unacceptable for patches to be subjected to high tire pressure tactical aircraft like the F-4.

4. Polymer Repair Materials

Polymers have been used with varying degrees of success for repairs to bridge decks, pavements and structural members. High strength, variable cure times and excellent bonding properties make polymers likely candidates for repair materials. Polymers either neat, with reinforcement or with aggregate have been studied extensively for possible application to repair of weapon damaged runways and conventional pavements (References 13, 15, 39, 41, 52, 54, 55, 56, 57, 58, 59, 60, 61, 62, and 63). Objections to polymers have centered on cost, variable environmental effects, shelf life and general complexity for use by unskilled labor. Further research is being conducted by the Air Force in this area.

5. Miscellaneous Repair Materials

a. Magnesium Phosphate Cements

Two types of magnesium phosphate cement are available on the market. One version developed by Republic Steel Corporation consists of a magnesium aggregate and a liquid phosphate solution which are

combined to form a fast setting, high strength cement. This product is marketed under a variety of trade names such as Darex 240, Bostik 275 and FC-100 by various Republic Steel licenses. Another version of magnesium phosphate cement is marketed by Set Products under the trade name Set-45. This product consists of a dry chemical cement to which water is added.

The fast setting cement developed by Republic Steel consists of a magnesia aggregate and a complex phosphate liquid solution which reacts as follows:

$$\text{Complex Phosphate} + M_gO \quad M_g NH_4 PO_4 \cdot 6H_2O + NH_3$$

The result of this reaction is primarily a magnesium ammonium phosphate hydrated salt and ammonia (Reference 64). The reaction is very rapid allowing only 5 to 7 minutes working time at 70°F. Strength gain is also rapid with compressive strengths of 1620 psi at one hour (Reference 64) and 2700 psi at 2 hours (Reference 22) being reported. The set time and rate of strength gain both decrease with decreasing temperature. Also the strength reportedly decreases rapidly if the mix is contaminated with water.

The material has excellent bond strength with Portland cement concrete, wood, paper, glass and some metals (Reference 64). However, the material does not bond to asphalt and this limits its application in pavement repair.[d] Excellent bond to Portland cement concrete has been confirmed by testing at the Waterways Experiment Station[e] and by Pike and Baker (Reference 22).

Republic Steel's fast setting chemical cement has been used for general highway patching in several locations. Mixing has been accomplished using paddle, ribbon and concrete mixers. A 20-foot section of interstate overpass at Warrensville, Ohio was successfully repaired using a Reed Guncrete machine to gun the cement into place. Temperature was 31°F and the repair was opened to traffic within two hours (Reference 65 and 66).

Set Products reports compressive strengths of 1950 psi in 45 minutes and flexural strengths of 826 psi in 3 hours for their product. Good bond strength is also claimed with concrete, masonry, wood and steel but no information is available concerning bond with asphalt. SET-45 is provided in 50 pound sacks and requires 1/2 gallon of mixing

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[d] Private communication with Mr. Wilbur J. Priver, the Upco Company.
[e] Test results provided courtesy of Mr George Hoff, WESS Concrete Laboratory.

water per sack. At lower temperatures, setting is delayed and strength gain is slowed. At 32°F the setting time can be expected to be approximately one hour, and the compressive strength will be about 700 psi after 1½ hours.[f]

Magnesium Phosphate cement's rapid strength gain is sufficient for this study, but its usefulness is impaired by high cost, short working time and sensitivity to water. It appears to be an excellent, high quality patching material for concrete pavements but of doubtful usefulness with bituminous pavements.

c. Petroset RB

Phillips Petroleum Company markets an emulsified rubber, Petroset RB, for stabilization of aggregate. Aggregate is first sprayed with ammonia and then sprayed with an emulsified rubber solution which breaks upon contact with the ammonia. Nielsen and Cassino (Reference 15) found that the strength of this rubber stabilized aggregate was very low and unsuitable for expedient repair of runways.

d. Unsurfaced Aggregate

The 1975 Eglin AFB field tests (Reference 3) successfully used compacted 3/4 inch graded aggregate to carry F-4 traffic. An 18 inch layer of aggregate, compacted in two lifts, was capable of carrying F-4 traffic over a saturated sandy clay subgrade (CBR of 0). Whenever minimum compaction levels were not obtained in these tests, catastrophic failures occurred.

Unsurfaced aggregate was unable to take F-4 traffic in the 1974 Tyndall AFB field tests (Reference 7), but this was due to insufficient compaction. Compaction had only been applied on the surface of the aggregate and no strength in depth had been built up by placing and compacting several lifts of aggregate.

A compacted, well graded base course quality aggregate can structurally support aircraft traffic without any surfacing. Individual aggregate particles will be loosened by traffic and will pose a potential foreign object damage (FOD) hazard to aircraft. A membrane such as T-17, can be used as a surface to prevent FOD problems but will not contribute to the strength of aggregate.

e. Landing Mat

The 1965 Eglin AFB tests tried three different types of landing mat: AM-2, Air-Dek and T-11 (Reference 3). These mats offered dependability, weather tolerance, ease of use and load carrying

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[f] Information provided by Set Products, Inc.

capacity superior to any of the fast curing cements or asphalts tested. AM-2 was judged to be the best of the three mats tested and has become the standard surfacing in the USAF repair system (References 4 and 6).

A considerable amount of AM-2 is in stock, but other types of landing mat may prove better suited for expedient repairs to damaged runways. Preassembled mat patches such as the Class 60 trackway used by the United Kingdom and Norway reduce manpower and equipment support requirements (Reference 14). The Truss Web or MX-19 mat offer more load carrying capacity than the current AM-2.

Small patches of mat can be assembled to cover a repair area, but they may be unsuitable for the small crater repairs considered in this study. Current regulations direct that mat be assembled across the entire width of the repair section which is not practical for small repair areas. The Norwegians ramp all sides of their repair mat and accept the possibility of axisymmetric loading from one wheel crossing the mat while the other wheel remains on the pavement (Reference 67). The most pressing question is whether aircraft can sustain the dynamic loads of crossing several small patches in succession. Recent analytical work by Boeing Corporation under contract to CEEDO indicates that existing aircraft have a very limited capability to operate over landing mat placed directly on the pavement because of roughness. Until this question is resolved, landing mat cannot be considered as a viable repair surfacing for small craters.

f. Precast Slabs/Flush Mounted Mats

The objections to the roughness associated with landing mats can be minimized by either trimming the mat or the crater so that mat patches fit flush with the surrounding pavement. If the crater is trimmed to a regular pattern precast slabs also become a feasible repair method. These approaches require extensive, precise cutting in the field.

At the Eglin AFB tests (Reference 3) tests were conducted which cut mat to fit the repair craters. It rapidly became apparent that placing the mat over the crater was a much more feasible approach than cutting the mat.

An alternative approach would be to cut the pavement around the crater to a regular shape so that the mat patch (or precast slab) can be placed flush. This approach has not recieved much serious attention in the past because of generally slow saw rates, amounts of water used with resulting softening of the subgrade, congestion at the crater and precision of measurements required. Alternatives to saws would include explosive rock drills with hydraulic rock splitters and hydraulic

concrete breakers. Precast slabs have been used for repair of highways with some success but replacement of slabs averaged 1½ hours not including the time to make the saw cuts in the pavement (Reference 68).

Flush mounted structural systems are conceptually attractive from several points of view. Actual implementation in the field would be difficult because of the amount of precise cutting and careful leveling that is required.

g. Thermoplastic and Silicone Rubber Materials

Raven Industries tested several thermoplastic materials (materials which soften when heated); however, slow cooling rates and consequently slow strength gain were unacceptable (Reference 52). Also a silicon rubber material was investigated but did not appear promising.

6. Selection of Materials

Table 7 summarizes the strength characteristics of several rigid paving materials discussed earlier. Of these materials, Type I portland cement with a sodium metasilicate accelerator, regulated set cement, high alumina cement with lithium carbonate, Fast Fix cement, VHE, and magnesium phosphate cements have the most promise of meeting the compressive strength requirements of 1400 psi in 2 hours.

Regulated set cements are being extensively investigated by the US Army Corps of Engineers so they will not be included in this study. Fast fix cements have already been studied in depth for expedient airfield repair, and little additional information could be added by further study. The VHE cement from US Gypsum Company is not available commercially so it also will not be considered further. The remaining materials, accelerated Type I cement, accelerated high alumina cement and magnesium phosphate cements offer enough promise to warrant further laboratory testing.

Conventional asphalt materials are unacceptable for repairs because of heating requirements for hot mix and lack of stability in conventional cold mixes. Several commercial cold mix asphalt materials offer some promise of combining adequate stability, no curing requirements and limited weather tolerance. These products are Amalgapave, Zor-X, and Future Patch. These materials can be handled with conventional construction equipment but require compacted base courses to withstand the required loads.

The following materials were selected for further laboratory testing:

1. Type I portland Cement with a sodium metasilicate accelerator.
2. High alumina cement with a lithium carbonate accelerator.
3. Magnesium phosphate cement.
4. Future Patch asphalt product.
5. Zor-X asphalt product
6. Amalgapave asphalt product.

## TABLE 7. SELECTED COMPRESSIVE STRENGTHS (PSI)

| Material | Reference | 1 Hr | 2 Hr | 4 Hr | 8 Hr | 24 Hr | 28 Day |
|---|---|---|---|---|---|---|---|
| Type I PC | 26 | - | - | - | 100 | 2150 | 7950 |
| Type I PC+SM | 25 | 700 | 1400 | 1750 | - | - | 2900 |
| Type III PC | 26 | - | - | - | 550 | 4850 | 8050 |
| Type III PC + $CaCl_2$ | 26 | - | - | - | 2300 | 5300 | 10600 |
| Special PC | 26 | - | - | - | 3350 | 9100 | 10950 |
| Reg Set | 22 | - | 360 | 2100 | 3200 | 4100 | - |
| Reg Set | 25 | 850 | 1100 | 1200 | - | 2200 | - |
| High Alumina | 26 | - | - | - | 9650 | 11400 | 14000 |
| Lumnite | 22 | - | - | - | 20 | 5200 | 7700 |
| Fondu | 22 | - | - | 50 | 3600 | 6200 | 9600 |
| Fondu + $Li_2CO_3$ | CD | 1850 | 3000 | - | - | 4800 | 7800 |
| Fast Fix 1 | 18 | 1800 | 2310 | 1920 | - | - | - |
| Fast Fix 3 | 18 | 1789 | 1515 | 1699 | - | - | - |
| VHE | PD | - | - | 3650 | - | 4290 | - |
| Magnesium Phosphate Cement | | | | | | | |
| Republic Steel | PD | 1620 | 2460 | - | - | 5530 | - |
| Set Products | CD | 2300 | - | - | - | 6375 | 8470 |

PC — Portland Cement
$CaCl_2$ — Calcium Chloride
SM — Sodium Metasilicate

$Li_2CO_3$ — Lithium Carbonate
Special PC — Finely ground cement, Specific surface 7420 $cm^2/g$

CD — Company supplied data
PD — Private Data

SECTION IV

## AMALGAPAVE LABORATORY TESTS

A limited laboratory investigation was undertaken to examine Amalgapave. The objective of this investigation was to determine if the hardener Diazite in Amalgapave improved the performance of cold mix asphalt, to examine the effect of varying Diazite and bitumen contents and to determine the effects of compaction effort on Amalgapave.

Bray Oil's Amalgapave product consists of a well graded aggregate, SC-250 liquid asphalt and a hardener Diazite. Amalgapave may be obtained premixed from licensed plants in California, or the individual components may be obtained separately and mixed at the job site. The latter option was selected for the laboratory investigation.

Bray Oil Company provided a sample of the hardener Diazite. The material is a black powder with the gradation shown in Figure 7. The larger fragments are hard, have a bright shiny luster and show conchoidal fracture. The material is soluble in trichloroethelyne, and Bray Oil reports the specific gravity to be 1.02. Bray Oil describes the hardener as a "polymerized petroleum hydrocarbon which utilizes a chemical reaction, initiated upon compaction of the mix, to toughen and solidify liquid asphalt."

Bray Oil believes that not all SC-250 liquid asphalts are compatible with the hardener Diazite.[g] SC-250 for this laboratory testing was purchased from Bray Oil's recommended source, Berk Oil Company of California. Table 8 summarizes testing on this liquid asphalt.

The aggregate for this testing was purchased from a local supplier. The gradation, shown in Figure 8, was within limits suggested by Bray Oil. Table 9 summarizes testing on this aggregate.

The Marshall mix design method as described in Reference 44 and 68 was selected to evaluate test mixtures. Samples for testing were prepared by first mixing the hardener and aggregate and then adding and mixing the SC-250 liquid asphalt. All mixing was done with a laboratory mechanical mixer. The samples were then compacted at room temperatures on the Corps of Engineers gyratory compaction apparatus with 200 psi pressure, 1° gyratory angle and 30 revolutions. Calculation of voids total mix and percent voids filled with bitumen was in accordance with MIL-STD-620A, method 101 using the saturated surface dry specific gravity and ASTM-D-2041 maximum theoretical specific gravity for computations. Marshall stability and flow (ASTM-D-1559) were run at room temperatures, thereby providing higher stability and lower flow values than standard.

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[g] Private communication with Mr Eugene Slaby of Bray Oil Company.

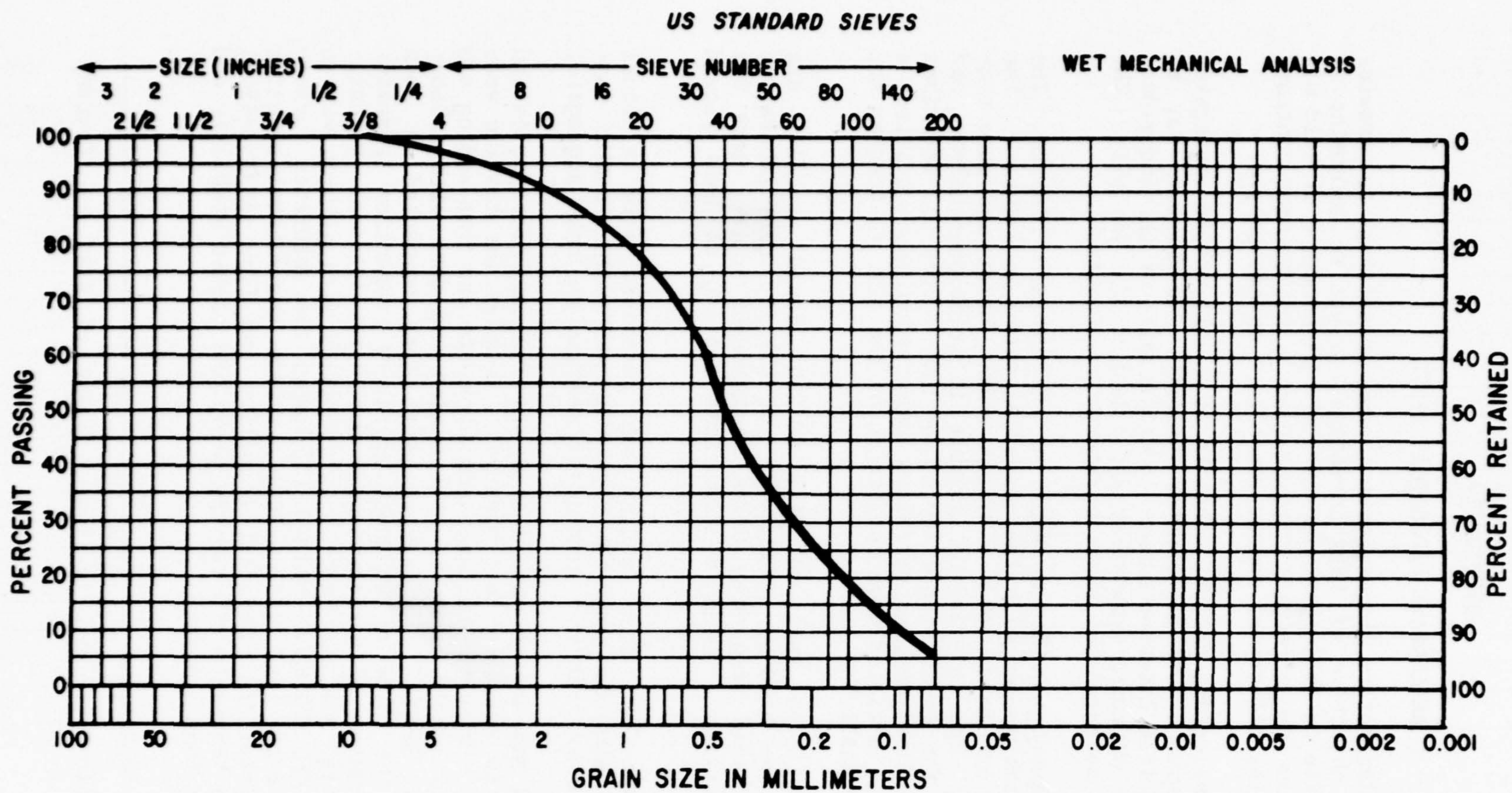



Figure 7. Gradation of Diazite Hardener

TABLE 8. PROPERTIES OF SC-250 LIQUID ASPHALT

| | Berk SC-250 | ASTM D-2026 Min | ASTM D-2026 Max | Astm Test |
|---|---|---|---|---|
| 1. Kinematic Viscosity, 60°C | 470 CST | 250 | 500 | D2170 |
| 2. Specific Gravity | 0.978 | - | - | D70 |
| 3. Total Distillate to 360°C | 4% | 4 | 20 | D402 |
| 4. Asphalt Residue of 100 Per | 80% | 60 | - | D243 |

TABLE 9. AGGREGATE PROPERTIES

| | Coarse Fraction[a] ASTM C-127 | Fine Fraction ASTM C-128 |
|---|---|---|
| 1. Bulk Specific Gravity | 2.707 | 2.688 |
| 2. Bulk Specific Gravity (SSD)[b] | 2.728 | 2.701 |
| 3. Apparent Specific Gravity | 2.764 | 2.488 |
| 4. Absorption (%) | 0.76 | 0.51 |
| 5. Unit Weight (PCF) | 168.9 | 167.7 |

[a] Retained on Number 4 Sieve

[b] Saturated Surface Dry

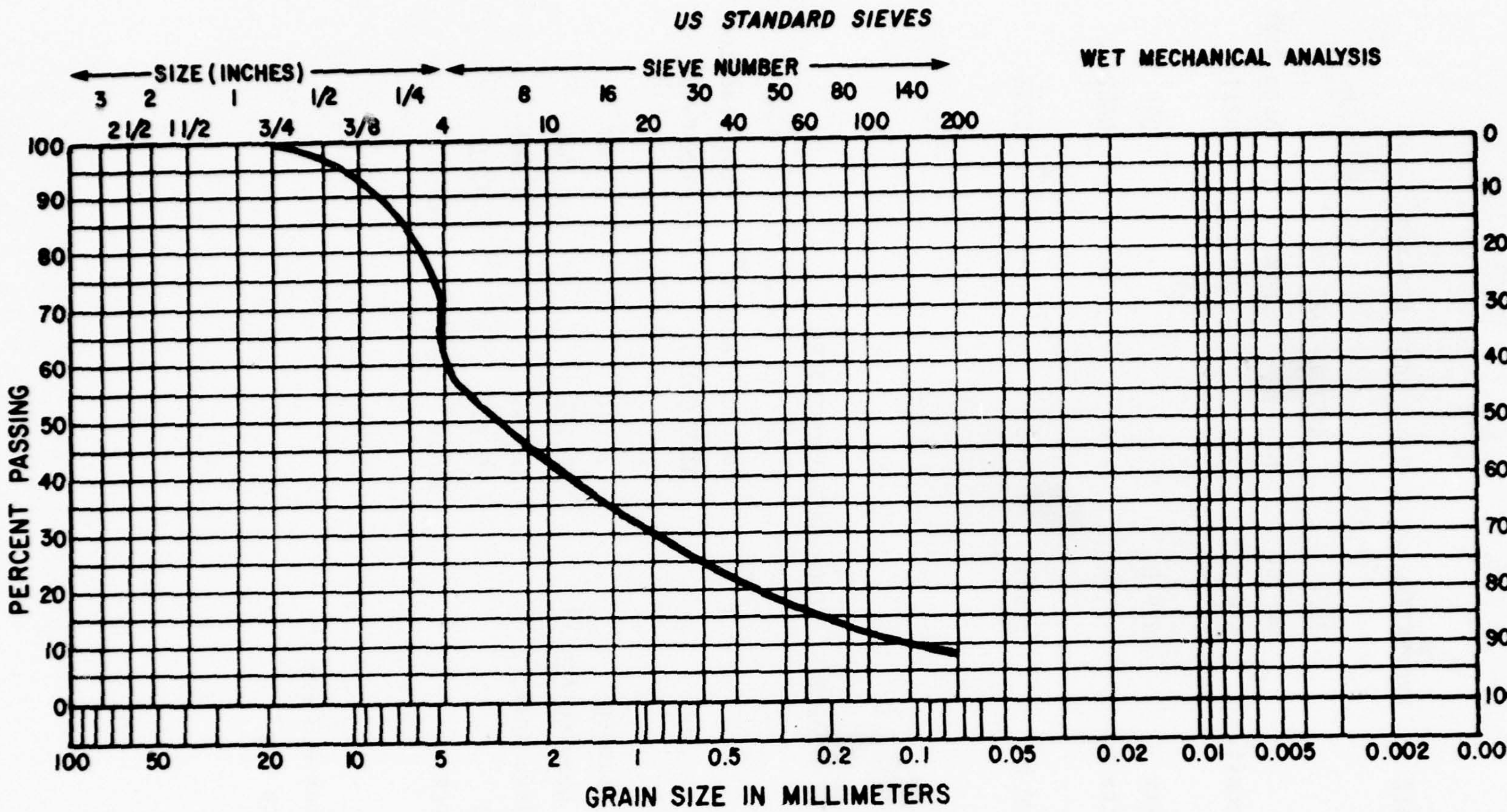



Figure 8. Amalgapave Aggregate Gradation for Laboratory Tests

Specimens heated in a water bath to the standard temperature of 140°F were very soft and deformed under light finger pressure. A tabulation of all test results can be found in Appendix A.

Diazite content of samples is expressed as a percent of aggregate weight, and SC-250 content is expressed as a percent of the total sample weight. Both the SC-250 and diazite are soluable in trichloroethelyne which is used as a solvent for determining butimen content in the laboratory. All bitumen contents from the laboratory included both SC-250 and Diazite. To obtain the percent SC-250 in a sample, the Diazite originally mixed in the sample was used to calculate a percent Diazite by weight of total sample, and that was subtracted from the percent bitumen by weight of total sample calculated in the laboratory.

Figure 9 shows results of tests on samples at varying contents of SC-250 with and without Diazite. Samples with Diazite consistently developed higher stability values. This is confirmed again in Figure 10 where samples with Diazite have up to 30 percent higher stability values than those without Diazite.

Figure 10 presents the results of testing on samples with 0 to 4 percent Diazite prepared with nominal 5.0 and 5.5 percent SC-250 contents. Also the difference between the laboratory bitumen content and the calculated SC-250 content is shown in Figure 10. Increased Diazite content decreases unit weight and increases flow. There is a definite optimum Diazite content for maximum stability values in Figure 10. The mixtures containing 5.0 percent SC-250 are deficient in bitumen as indicated by high percent voids total mix and low percent total voids filled with bitumen. The mixture with 5.5 percent SC-250 has the same problems when Diazite contents reach 2 to 3 percent. The gyrographs from the gyratory compaction apparatus for samples prepared at 6.35 percent SC-250 and 2.5 Diazite showed signs of flushing indicating an excess of bitumen. Optimum mix design for this particular aggregate would appear to be 2 to 2.5 percent Diazite to obtain maximum stability and 5.5 to 6.0 percent SC-250 to meet voids criteria. Table 10 compares test results for a 2.5 percent Diazite and 5.5 percent SC-250 mix design for Amalgapave (extrapolated from Figure 10) and design criteria from the Asphalt Institute and AFM 88-6. (Reference 44 and 70).

Figure 11 presents the results of varying compactive efforts on a mix with 5.5 percent SC-250 and 3.5 percent Diazite. Increased compaction effort could bring test results within the void criteria of AFM 88-6 for surface course, but stability values are still well below the minimum.

Diazite is effective in raising stabilities of mixtures of SC-250 and aggregate; however, values are still well below standard criteria for hot mix bituminous concrete. Mix design for Amalgapave must

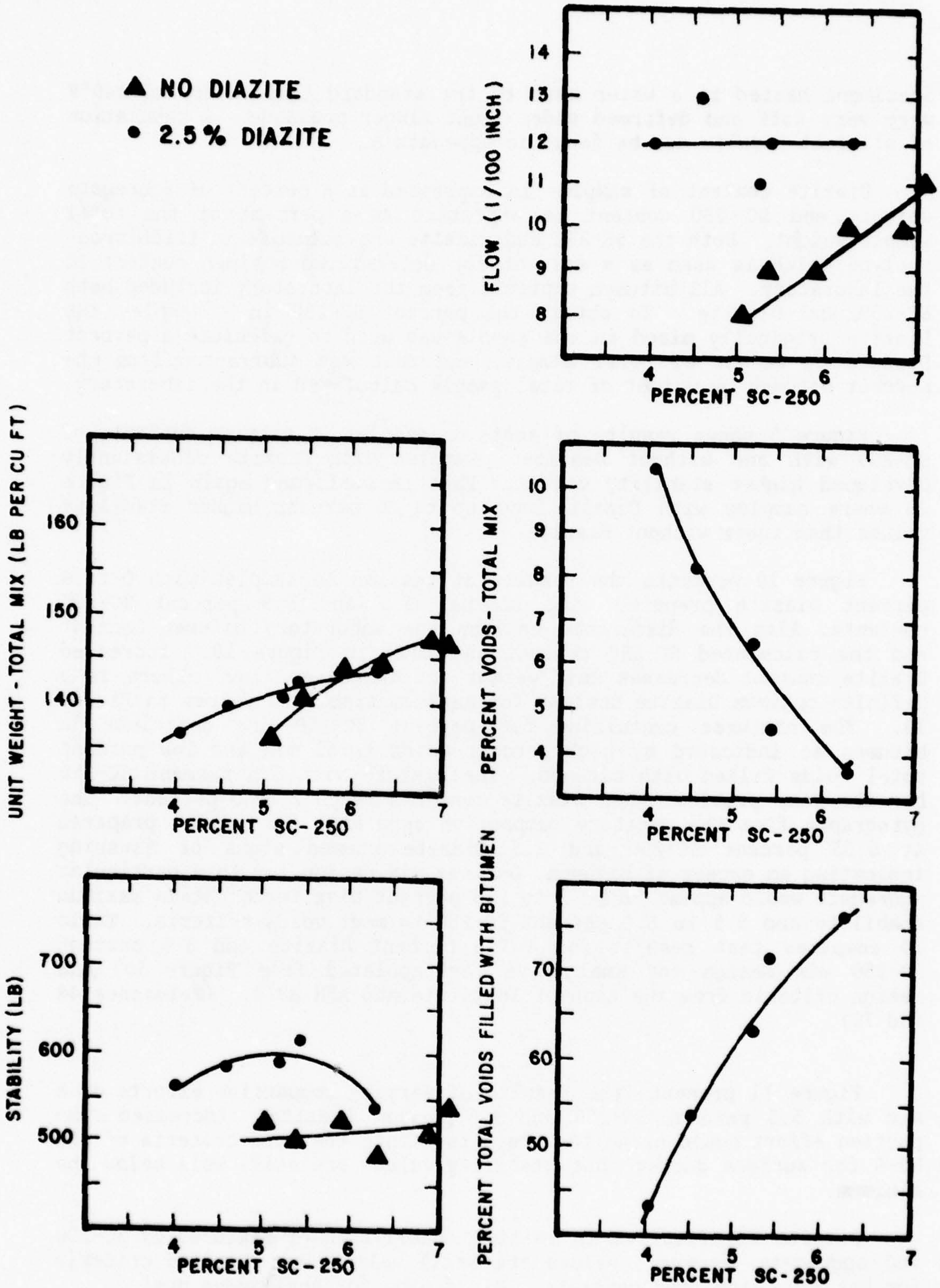



Figure 9. Tests With and Without Diazite

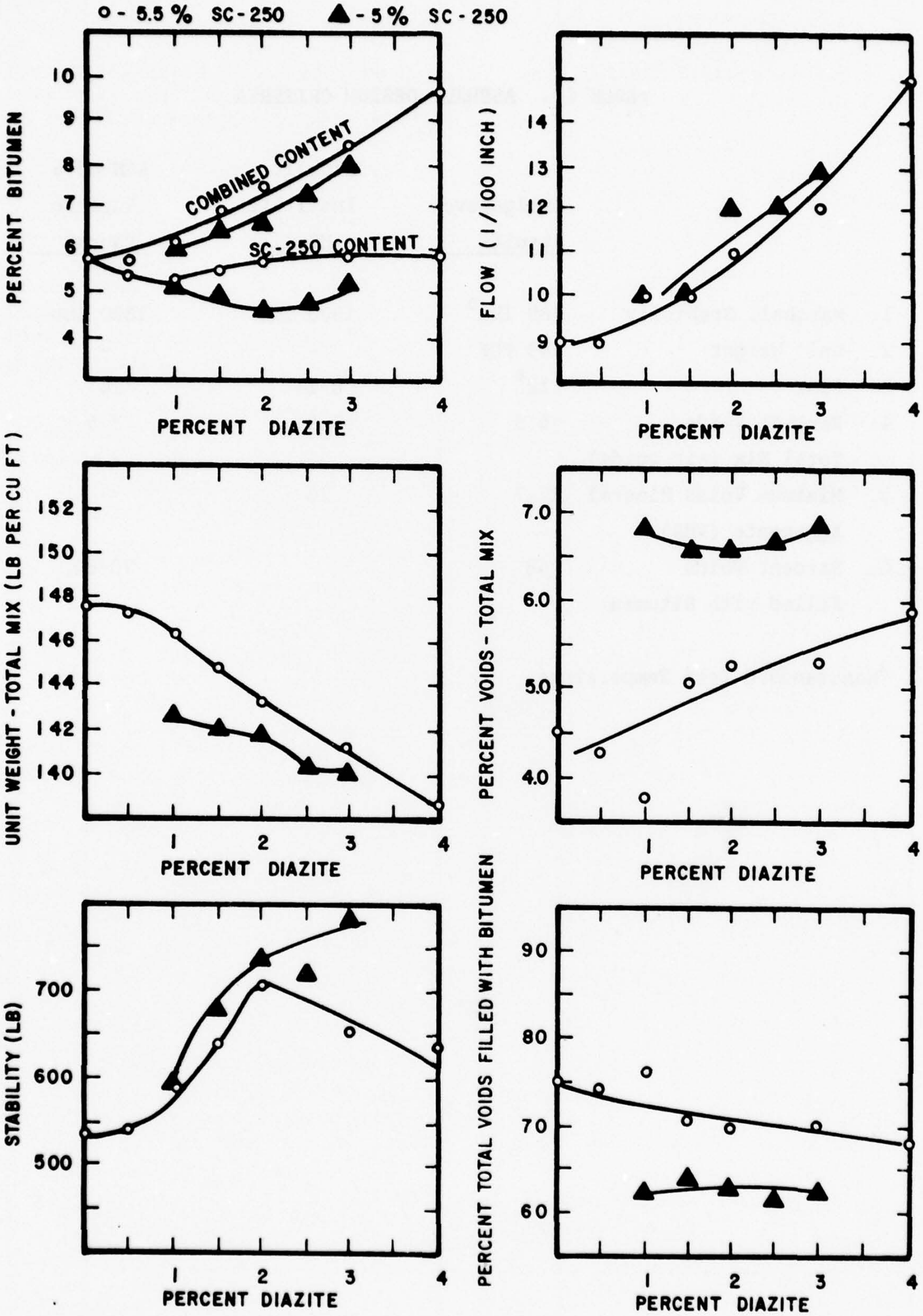



Figure 10. Effect of Varying Amounts of Diazite

TABLE 10. ASPHALT DESIGN CRITERIA

| | Amalgapave Results | Asphalt Institute MS-11 | AFM 88-6 Surface Course |
|---|---|---|---|
| 1. Marshall Stability | 680 lbs[a] | 1800 lbs | 1800 lbs |
| 2. Unit Weight | 143 PCF | - | - |
| 3. Flow | 12[a] | 8-14 | 16 |
| 4. Percent Voids Total Mix (air voids) | 5.3 | 3-5 | 3-5 |
| 5. Minimum Voids Mineral Aggregate (VMA) | 17.7 | 16 | - |
| 6. Percent Voids Filled with Bitumen | 68 | - | 70-80 |

[a]Nonstandard Test Temperature

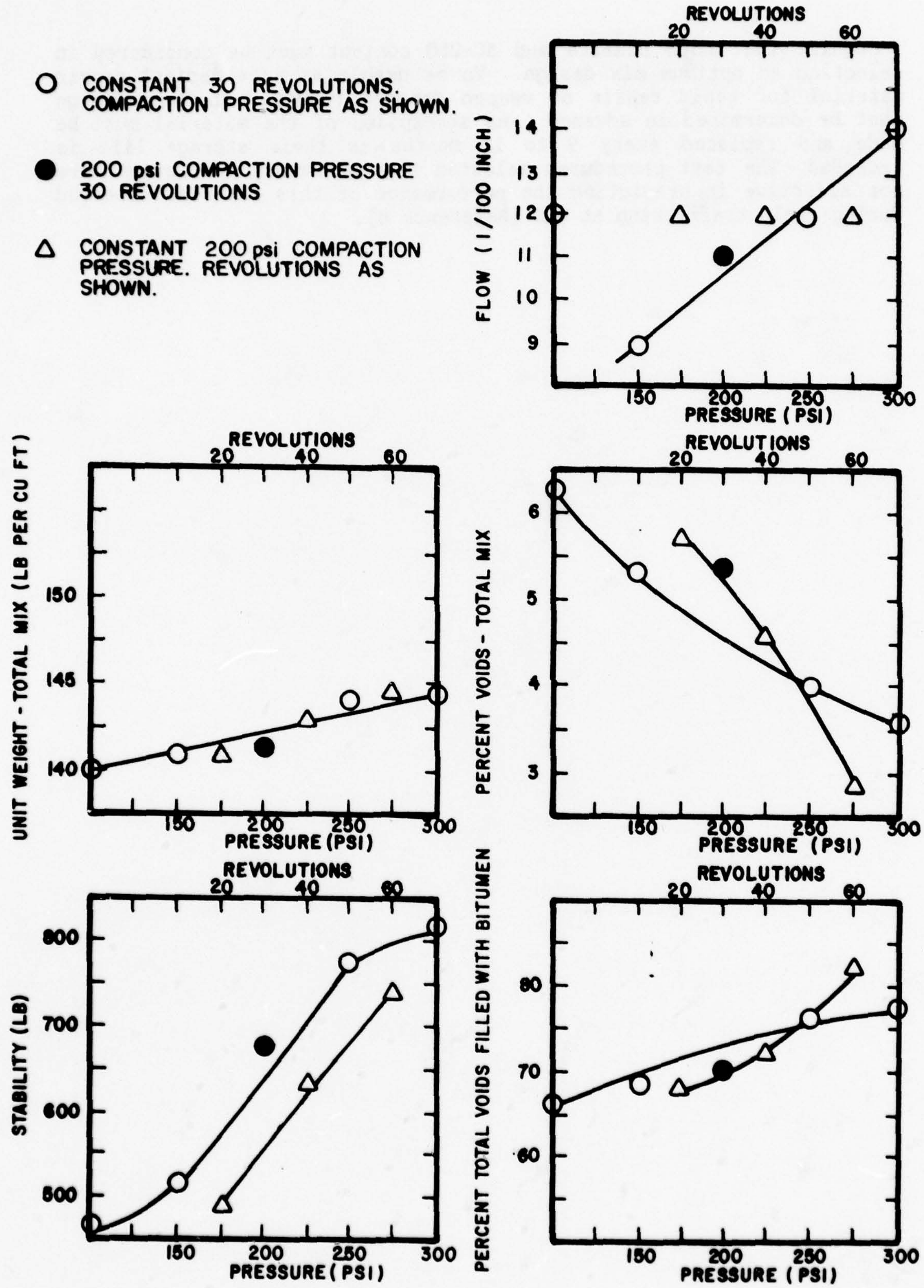



Figure 11. Effect of Varying Levels of Compaction

recognize that both Diazite and SC-250 content must be considered in selecting an optimum mix design. To be usable as an expedient repair material for rapid repair of weapon damaged runways, the mix design must be determined in advance, and stockpiles of the material must be made and replaced every 9 to 12 months as their storage life is exceeded. The test procedures selected for laboratory evaluation were not effective in predicting the performance of this material observed during field trafficking at WES (Reference 8).

## SECTION V

## LABORATORY TESTING OF FUTURE PATCH AND ZOR-X

Samples of Future Patch and Zor-X were compacted on the Corps of Engineers Gyratory Compaction Apparatus at 200 psi compaction pressure, 1° gyratory angle and 30 revolutions. A Marshall Series, as described in Section IV, was run on these samples. The results are shown in Table 11. The aggregate gradation from these samples is shown in Figure 12.

The results of the Marshall tests and the aggregate gradations indicate that Zor-X and Future Patch are similar materials. Each uses a fine, poorly graded aggregate and a high asphalt content. Existing test criteria would indicate the material would be very soft and easily rutted. This, at least for Future Patch, does not adequately describe the material's performance at the spall tests at WES (Reference 8). Improved criteria and test methods for evaluating asphalt patching materials are needed.

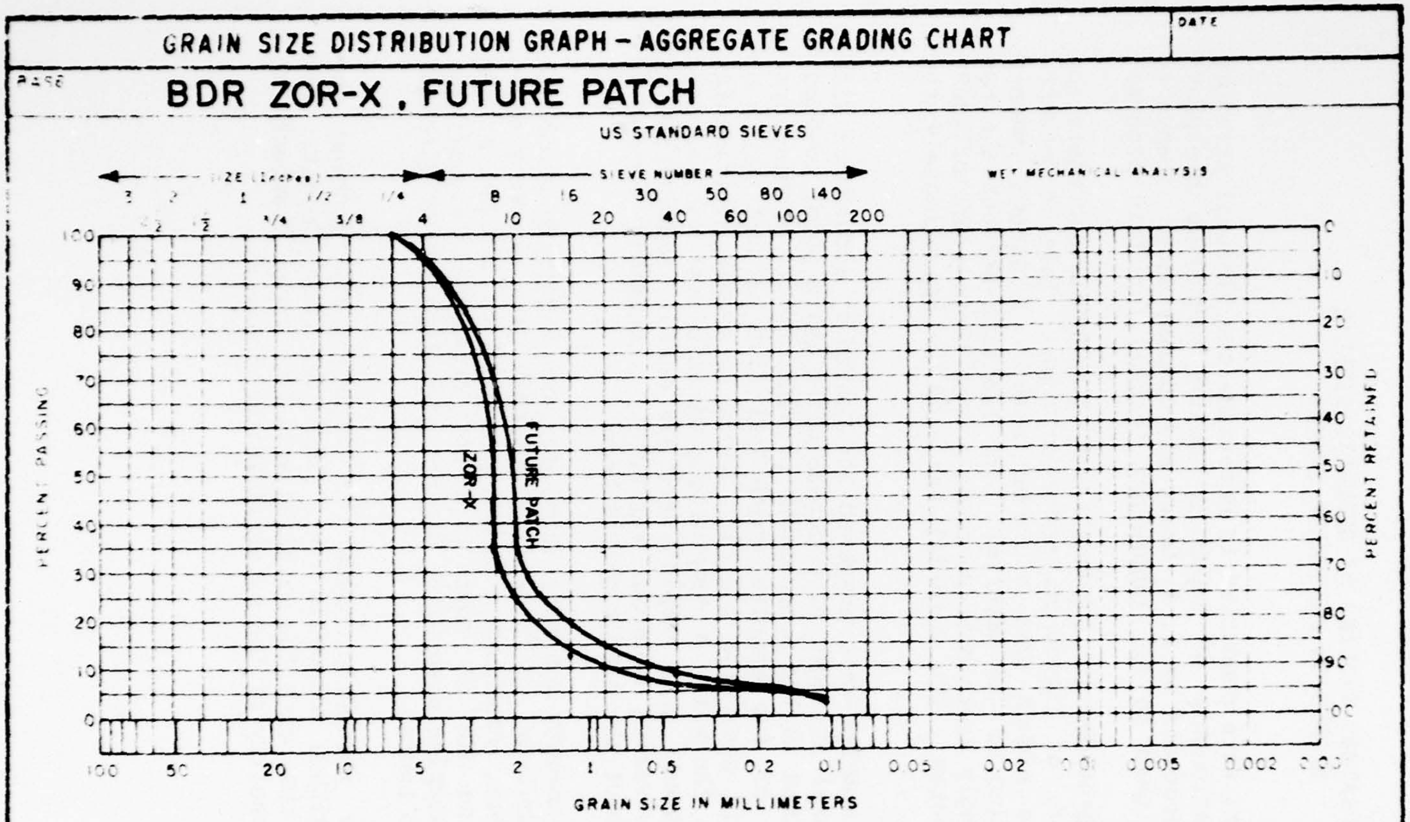
TABLE 11. TEST RESULTS FOR ZOR-X AND FUTURE PATCH

| Material | Asphalt Content[a] | Bulk Specific Gravity (SSD)[b] | Stability[c] | Flow[c] | Asphalt Penetration |
|---|---|---|---|---|---|
| ZOR-X | 7.6 | 2.036 | 638 | 11 | 343 |
| Future Patch | 8.1 | 2.021 | 831 | 10 | 395 |

[a] Percent total mix.

[b] SSD - Saturated Surface Dry.

[c] Run at room temperature.




| TEST PIT NR | SAMPLE NUMBER | $G_s$ | $W_L$ | $W_P$ | $I_P$ | CLASSIFICATION | REMARKS |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |

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Figure 12. Aggregate Gradation for Future Patch and ZOR-X

## SECTION VI

## LABORATORY TESTING OF REPUBLIC STEEL'S MAGNESIUM PHOSPHATE CEMENT

Laboratory tests were conducted to determine the flexural strength and cure time relationship of Republic Steel's magnesium phosphate cement. Darex 240 produced by W. R. Grace and Company under license to Republic Steel was used in all laboratory testing for this program.

Darex 240 was provided in 50 pound sacks of magnesia aggregate and one-gallon containers of liquid phosphate solution. These components were mixed for one minute with a mortar mixer. A strong ammonia accompanied the mixing of the material. The reaction between the two components was strongly exothermic reaching a peak temperature of 130°F in about forty minutes. The material hardened in approximately ten minutes.

Thirteen beam samples were prepared and tested in accordance with ASTM C-78 for flexural strength of concrete using third point loading. All samples were mixed in the proportions provided by the manufacturer with the exception of two samples which had five percent water by volume of the liquid phosphate solution added to examine detrimental effects of water on the mix. A very strong ammonia odor was released when beams were tested. All samples were air cured. Examination of the broken beams revealed numerous vesicules, presumably formed by ammonia gas, throughout the matrix of the beam.

The flexural strength and cure times for the magnesium phosphate cement beams are tabulated in Table 12. Strength gain was very rapid during the first hour, reaching a value in excess of 500 psi at one hour. Further curing for 24 hours did not result in significant strength gain. The samples with water did not show any loss of strength after curing for two hours.

This magnesium phosphate cement is capable of reaching the required strength within allowable cure times for this project. The very short working time with the material will be a major drawback for using any sizable quantity of the material in the field.

TABLE 12. FLEXURAL STRENGTH OF REPUBLIC STEEL'S MAGNESIUM PHOSPHATE CEMENT

| Sample | Cure Time (Min) | Flexural Strength (psi) |
|---|---|---|
| 1 | 44 | 436 |
| 2 | 58 | 550 |
| 3 | 60 | 503 |
| 4 | 87 | 499 |
| 5 | 93 | 503 |
| 6 | 116 | 516 |
| 7 | 126 | 526 |
| 8 | 151 | 561 |
| 9 | 153 | 498 |
| 10 | 1440 (24 Hrs) | 585 |
| 11 | 1443 (24 Hrs) | 517 |
| 12[a] | 122 | 520 |
| 13[a] | 123 | 554 |

[a] 5 percent water added to phosphate solution

## SECTION VII

## LABORATORY TESTING OF SET PRODUCTS' MAGNESIUM PHOSPHATE CEMENT

Laboratory tests were conducted on Set Products' Set-45 magnesium phosphate cement to determine flexural strength and cure time relationships and to determine initial and final set times. Set-45 was obtained in 50 pound sacks. The material tested had been stored in a warehouse for approximately one year.

Two samples, 6 x 6 x 5½ inches, were prepared by hand-mixing eight parts Set -45 to one part water. The sample was rodded 36 times. Initial and final set times were determined to be 13 and 15 minutes by ASTM C-403. The temperature of the samples rose from 88°F five minutes after mixing to 133°F 17 minutes after mixing.

Ten beam samples were prepared and tested according to ASTM C-78 to determine flexural strength. The material for these tests were mixed in a mechanical mortar mixer at the manufacturer's recommended proportion of 50 pound Set-45, 30 pound 3/8-inch uniform aggregate (pea gravel) and 1/2 gallon of water. All samples were air cured.

The results of this testing are shown in Table 13. Strength gain was unacceptably slow and did not reach 400 psi flexural strength after 24 hours of curing. Samples tested at 1, 1½ and 2 hours had no aggregate breakage; the samples at 3 hours had about 10 percent aggregate breakage and the samples at 24 hours had about 75 percent breakage. These low strengths are believed to be due to the age of the material. Further testing was discontinued because of the low strengths and apparently limited shelf life.

TABLE 13. FLEXURAL STRENGTH OF SET PRODUCTS' MAGNESIUM PHOSPHATE CEMENT

| Sample | Cure Time (Min) | Flexural Strength (psi) |
|---|---|---|
| 1 | 60 | 211 |
| 2 | 60 | 224 |
| 3 | 90 | 217 |
| 4 | 90 | 198 |
| 5 | 120 | 208 |
| 6 | 120 | 208 |
| 7 | 180 | 329 |
| 8 | 180 | 250 |
| 9 | 1440 (24 Hrs) | 398 |
| 10 | 1440 (24 Hrs) | 337 |

## SECTION VIII

## LABORATORY TESTING OF ACCELERATED PORTLAND CEMENT

Laboratory tests were conducted to determine strength gain of Type I portland cement with sodium metasilicate pentahydrate as an accelerator. Cement, sodium metasilicate, sand and water were mixed together to determine working time. This mixture hardened in about 15 minutes without any noticeable exotherm.

Four flexural beams were prepared and tested to determine flexural strength as required by ASTM C-78. Type I portland cement, sand and coarse aggregate were mixed in a 1:1.9:2.2 proportion by weight. The water cement (W/C) ratio for two beams was 0.50 and for the other two beams was 0.39. Fifty nine percent sodium metasilicate pentahydrate by weight of water was used as accelerator as recommended in Reference 25.

The beams with a 0.50 W/C ratio had flexural strength of 62 psi and 117 psi at 2 and 12 hours. The other two beams had flexural strengths of 54 and 42 psi at 2 hours.

These results were radically different from those in Reference 25 so the US Army Waterways Experiment Station Concrete Laboratory was contacted for assistance. From these discussions it was determined that, although high early strengths could be obtained with sodium metasilicate, exact proportioning must be matched to the specific cement being tested. The average Air Force civil engineering squadron would not have the test facilities to allow determination of sodium metasilicate proportioning for local cements. Testing of this material was discontinued because of the very precise proportioning required.

## SECTION IX

## LABORATORY TESTING OF ACCELERATED HIGH ALUMINA CEMENT

This section is based primarily on laboratory tests conducted by Mr Vince Cassino of the Eric Wang Civil Engineering Research Facility (CERF) under contract F29601-76-C-0015 (SS 05-07) to CEEDO. Mr Cassino's testing and analysis were provided to the Air Force in Reference 71. Some limited additional testing was performed by AFCEC. The results of all testing is tabulated in Appendix B and the performer of each test (CERF or CEC) is shown.

Lithium carbonate[h] ($Li_2CO_3$) has been identified as an avid accelerator for high alumina cement. Fondu high alumina cement[i] was used for all laboratory tests. Samples six inches in diameter and six inches deep were prepared and tested for initial and final set in accordance with ASTM C-403. Lithium carbonate was mixed with the cement and then water was added and mixed with the cement and accelerator for three minutes in a laboratory mixer. Batches consisted of 4000 grams of high alumina cement and 1600 grams of water. The initial and final set times for six different accelerator contents are shown in Figure 13. Small amounts of lithium carbonate dramatically decrease set times. Concentrations above 0.06 percent by weight of cement do not appear to have shortened set times further.

The very rapid set times caused by lithium carbonate make it desirable to find a retarder to slow down the reaction. Three retarders, two lignosulfates[j] and one hydroxycarboxyllic[k], were selected for testing from information provided by Lonestar Lafarge Company. Samples were prepared as before with 0.06 percent lithium carbonate and varying amounts of each retarder. The initial and final set times for each retarder are shown in Figure 14 (ASTM C-403). The Plastiment retarder was the most effective of the three, and, since it was available in a liquid form, it was also the most convenient to use. Both RDA S-2 and Marasperse C-21 were in powder form and were dissolved in water before mixing.

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[h] Manufactured by Lithium Corporation of America, Bessemer City, North Carolina.

[i] Manufactured by Lonestar Lafarge Company, Norfolk, Virginia.

[j] Marasperse C-21, American Can Company, Greenwich, Connecticut. RDA S-2, W. R. Grace Company, Houston, Texas.

[k] Plastiment, Sika Chemical Company, Lyndhurst, New Jersey.

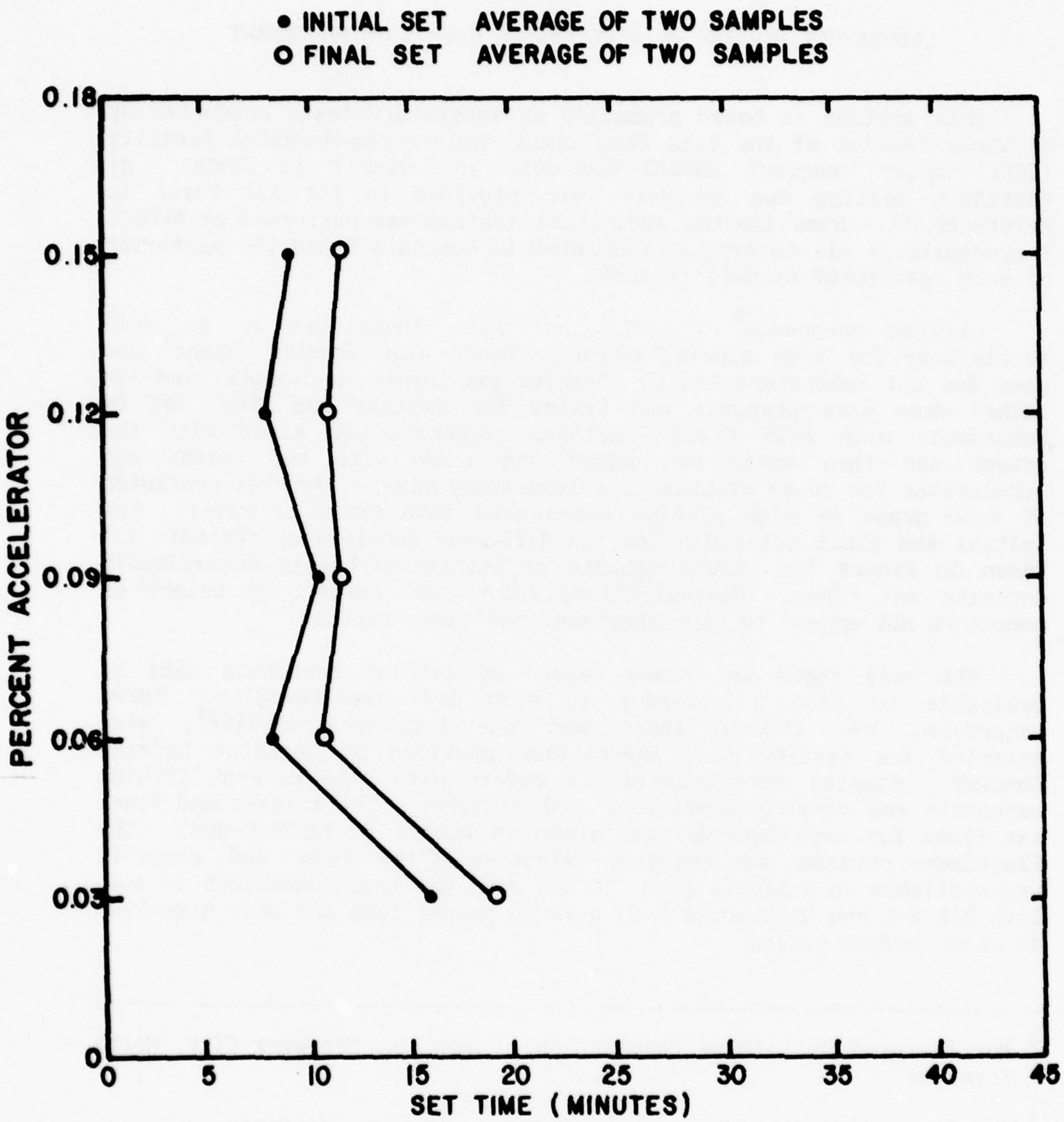


Figure 13. Effect of Lithium Carbonate on High Alumina Cement Set Times

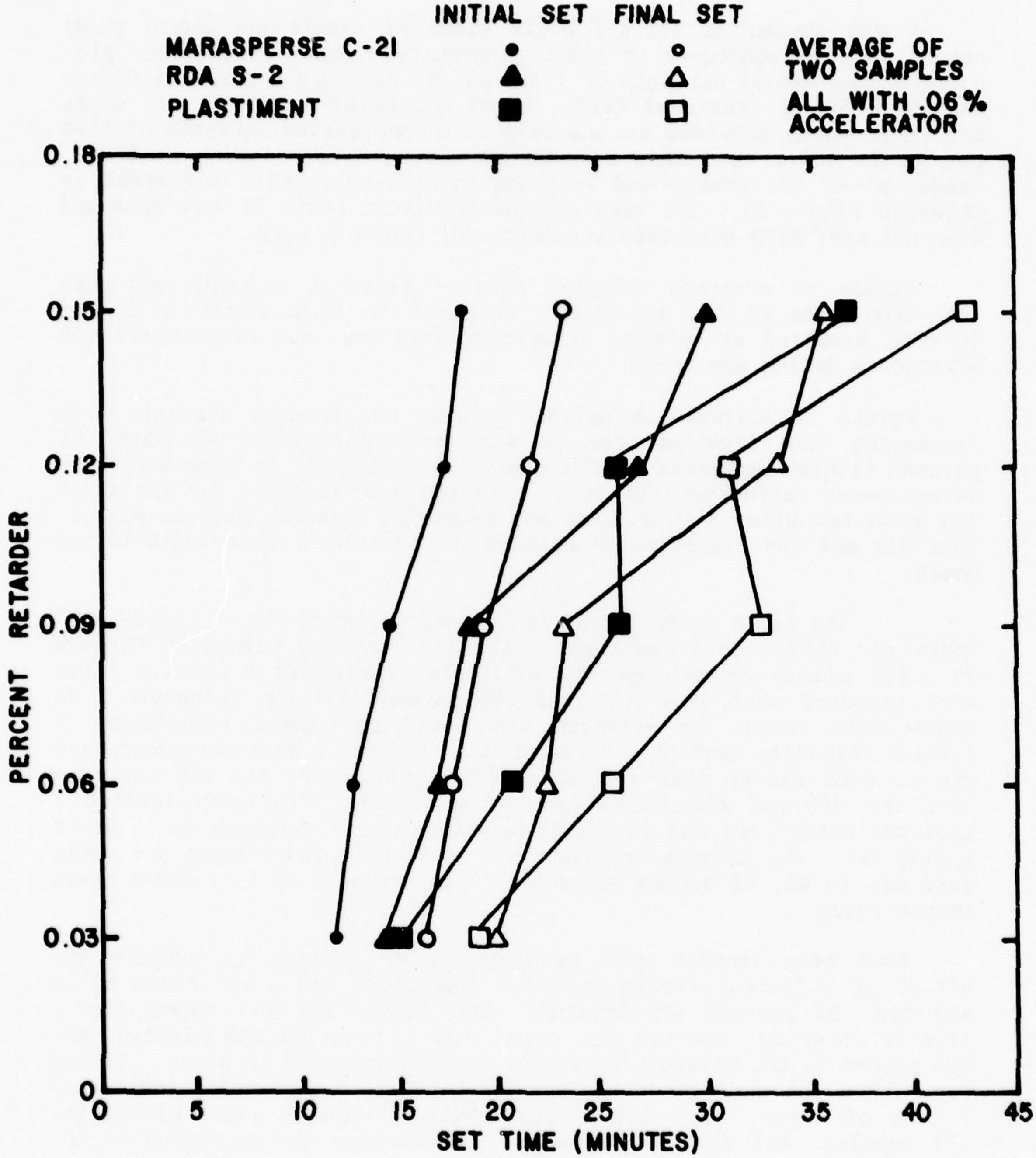


Figure 14. Effect of Selected Retarders on Accelerated High Alumina Cement

A mix design of 1:1.3:1.4 (10 sacks of cement per cubic yard) cement to fine aggregate to coarse aggregate without accelerator provided a compressive strength of 7,490 psi at 24 hours. This mix design was used for all tests at CERF. A mix design of 1:1.4:3.1 (7 sacks per cubic yard) provided an unaccelerated compressive strength of 5950 psi at 24 hours, and this mix design was used for testing at AFCEC. Gradation of the coarse and fine aggregate used by CERF and AFCEC is shown in Figure 15. The sand used in the AFCEC tests is very fine and does not meet ASTM gradation standards for concrete sand.

Figure 16 presents selected data of flexural strength[1] and cure time from tests at CERF and AFCEC. Points 1, 4, 5, 6, and 7 of Figure 16 were prepared at varying water/cement ratios, but results are too erratic to define any trend.

Points 10 through 18 define a curve of flexural strength with increasing cure time for the 10 sack per cubic yard mix with .06 percent lithium carbonate (.03 percent for point 18), no retarder and a water/cement ratio (w/c) of 0.4. Strength gain is rapid for the first few hours but after 3 to 4 hours any remaining strength gain is slight. This mix met the criterion of gaining 400 psi flexural strength in two hours.

The tests conducted at AFCEC used a leaner mix of concrete (7 sacks per cubic yard) and these tests are shown by points 25 through 33. For points 25 through 32, duplicate samples at a 0.4 w/c ratio were prepared with both .03 and .06 percent lithium carbonate. No appreciable change in strength was noted for these variations in lithium carbonate content. Strength gain for the 7 sack per cubic yard mix is much slower than the 10 sack per cubic yard mix and fails to meet the 400 psi flexural strength requirement. An unaccelerated 7 sack per cubic yard mix reached 448 psi flexural strength in 24 hours (point 33). The lithium carbonate did accelerate the 7 sacks per cubic yard mix to 44, 62 and 80 percent of this strength at 1, 2 and 4 hours respectively.

Four beam samples were prepared by Mr Cassino to examine the effect of different curing methods. The beams had a w/c ratio of .4 and had .03 percent accelerator. One sample was air cured with a plastic covering; one was air cured with wet burlap and plastic; one was placed in the moisture room; and one was immersed in water. Curing began when the surface of the samples began to change color indicating a loss of water. This was approximately 35 minutes after mixing for all samples. All samples reached a 155°F before the hardening of the concrete precluded further measurements.

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[1] Point numbers in Figure 16 correspond to the test numbers in Appendix B.

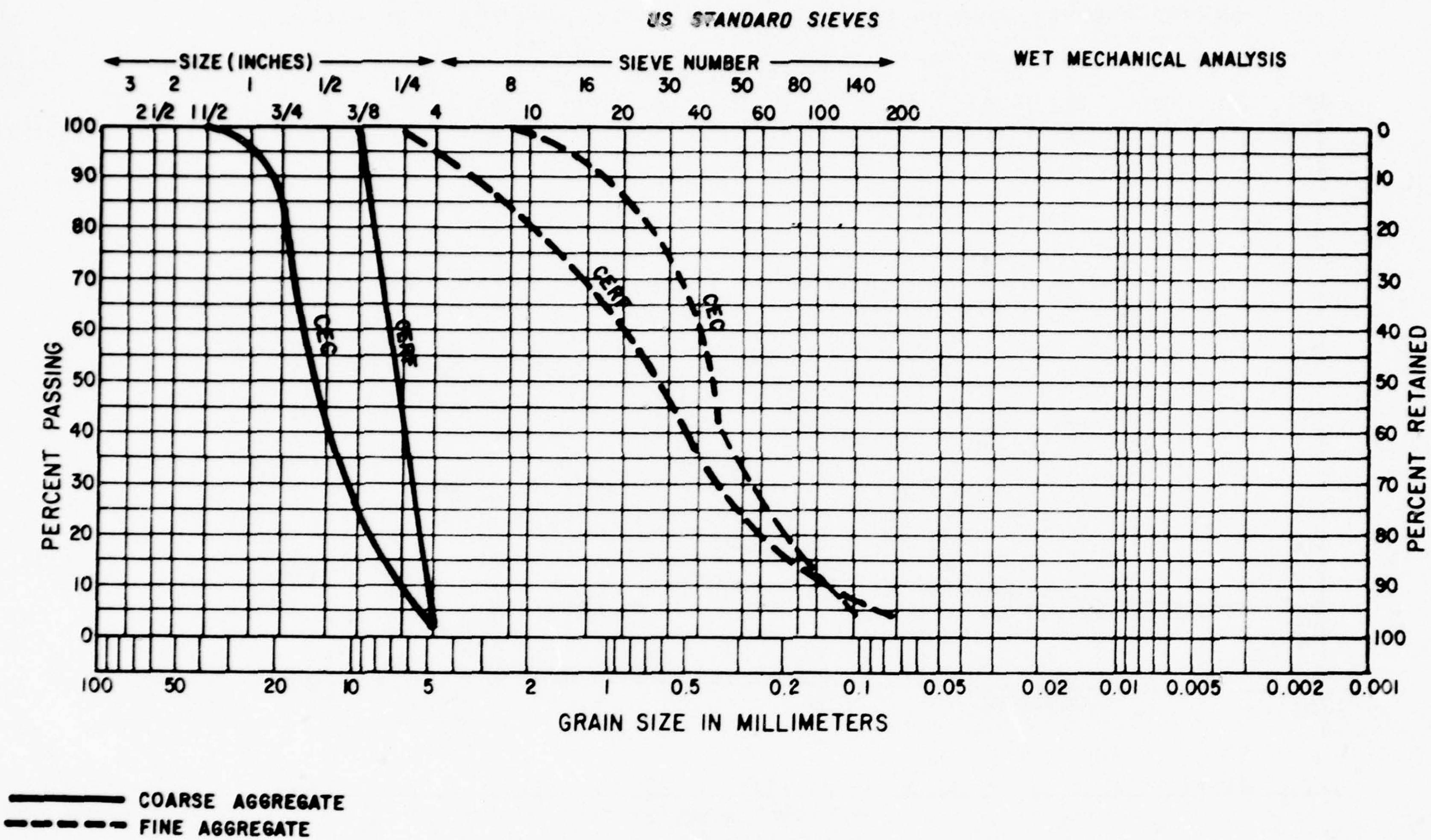


Figure 15. Cradation of Concrete Aggregate

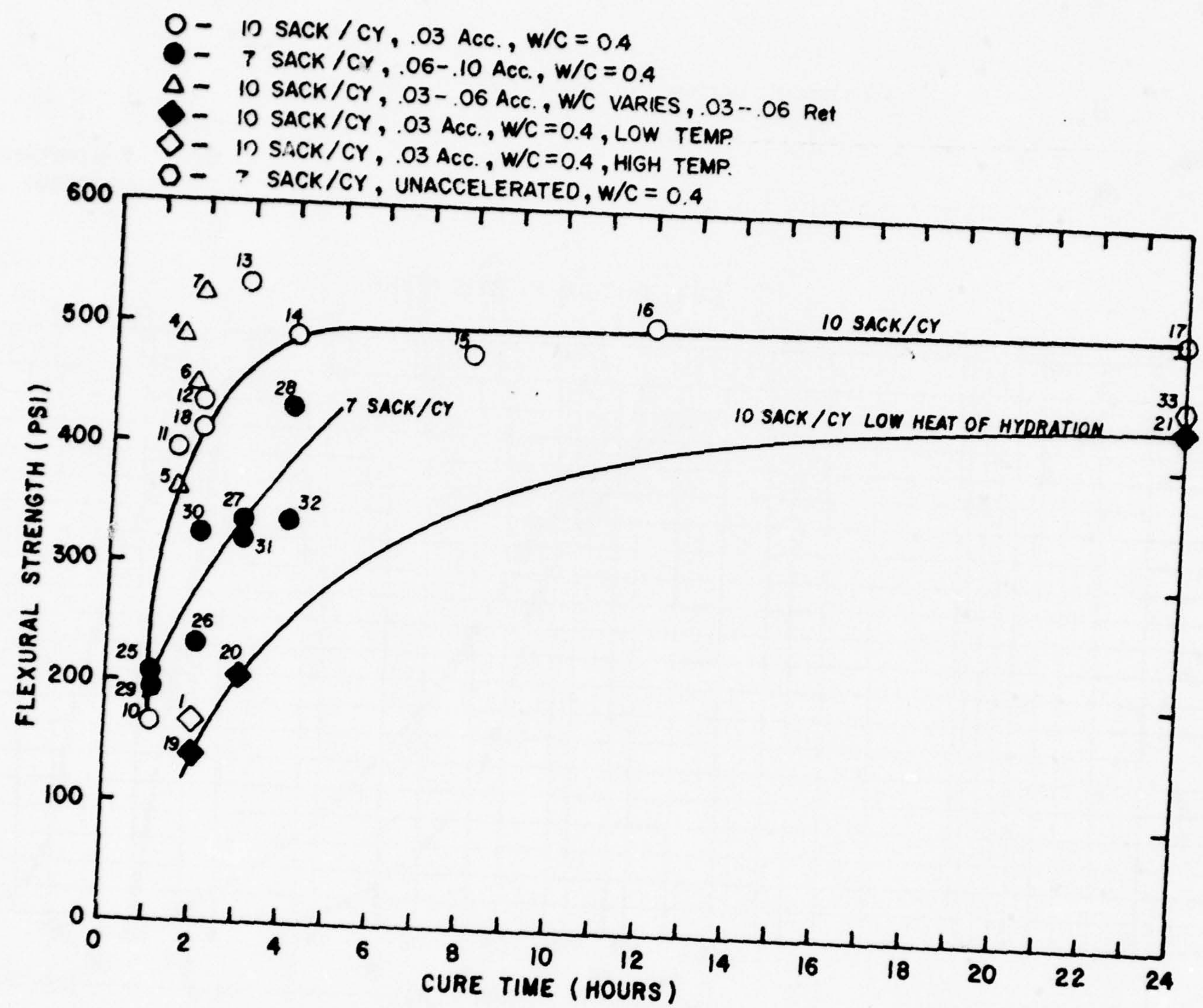


Figure 16. Flexural Strength of Accelerated High Alumina Cement

Two hours after mixing the flexural strength for the air cured beam was 410 psi; the air cured with burlap beam was 308; the moisture room beam was 72 psi; and the immersion beam was 78 psi. Mr Cassino believed that this decrease in strength was due to the cooling effects of the different cure methods. The wet burlap provided some moisture to cool the beam, and its strength was reduced 25 percent in comparison to the air cured beam. The moisture room and immersion cure methods could be expected to significantly lower the beam temperatures, and strengths from these two cure methods were only 20 percent of the air cured beam. All beams reached the same temperature (155°F) before being subjected to different cure methods (Reference 71).

Three beams with the same mix design were next prepared by Mr Cassino at 68°F ambient temperature (previously 72°F) and with the aggregate and water at 58°F (previously not recorded but judged to be higher). The temperature of the plastic concrete was recorded as before and only reached 100°F. The samples were air cured under plastic and reached flexural strengths of 148, 209, and 438 psi at 2, 3 and 24 hours. Points 19, 20 and 21 in Figure 16 show this radical reduction in strength due to lower temperatures. For comparison, point 18 was the identical mix and cure method from the beams prepared for the investigation of different cure methods.

Past field tests with fast setting cements such as Fast-Fix or Regulated-Set cement indicate that it is very difficult to proportion, mix, deliver and place fast setting concrete in the field. To reduce this materials handling problem, water/cement slurries have been pumped over preplaced uniform size aggregate and allowed to percolate through the aggregate to form the concrete repair cap. This reduces the quantity of materials to be mixed (no aggregate) and allows use of pumps to move the slurry, but it also increases the total amount of cement to be used (no fine aggregate to fill the aggregate voids) and reduces the strength. This approach of percolating a water/cement slurry through uniform aggregate was investigated by Mr Cassino for high alumina cement.

Molds 1 x 1 x 1 feet were filled with 1/2, 1 and 1 1/2 inch uniform aggregate to examine penetration of the Fondu slurry. A slurry with 0.4 w/c ratio, .06 percent lithium carbonate accelerator and .06 percent Plastiment retarder rapidly became too viscous to penetrate the aggregate. A second slurry with the accelerator reduced to .03 percent and retarder increased to .12 percent penetrated all three aggregate gradations. A third slurry with a w/c ratio of .37 penetrated the 1 1/2 and 1-inch aggregate but did not penetrate the full one-foot depth of 1/2 inch aggregate.

Duplicate flexural beams were prepared by pouring a slurry with a w/c ratio of 0.4, .03 percent accelerator and .12 percent retarder over the 1 1/2 and 1-inch aggregate. After two hours of curing the 1 1/2

aggregate beams had flexural strength of 200 and 180 psi, and the 1-inch aggregate beams had 240 and 250 psi flexural strengths. This is only half the strength obtained earlier with a conventional mix of cement, coarse aggregate and fine aggregate. The slurry concrete's lowered strength appears to outweigh its mixing and handling advantages, and no further work was done in this area.

Mixtures of portland cement and high alumina cement have rapid set times (Reference 23) and were investigated as a possible fast setting repair material for airfield repairs. Type I portland cement and high alumina cement were mixed in varying proportions. Initial and final set times were determined in accordance with ASTM C-403 but set times were very erratic. Figure 17 shows the results of this testing. Each point shown is the average of two specimens, but up to 100 percent variation occurred between the values of set times for some specimens.

Beams were prepared with a w/c ratio of .4, and a 10 sack per yard mix. The cement consisted of 80 percent Type I portland cement and 20 percent high alumina cement. At 24 hours the strength of these beams was only 146 psi; at 72 hours it was 437 psi; and at 168 hours it was 545 psi. There is insufficient strength in portland and high alumina cement mixtures to be usable for rapid airfield repair.

Lithium carbonate has been found to be a highly effective accelerator for high alumina cement. Variations in lithium carbonate from .03 to .10 percent do not appear to increase early strength. A retarder can be added to slow the speed of reaction but this also lowers strength. It is possible to meet the 400 psi flexural strength criteria in 2 hours, but temperature and cure method have a strong effect on this material. The speed of the reaction limits use of this material to small repair areas. Attempts to use a high alumina cement slurry poured over uniform aggregate and to use mixtures of portland cement and high alumina cement were unsuccessful.

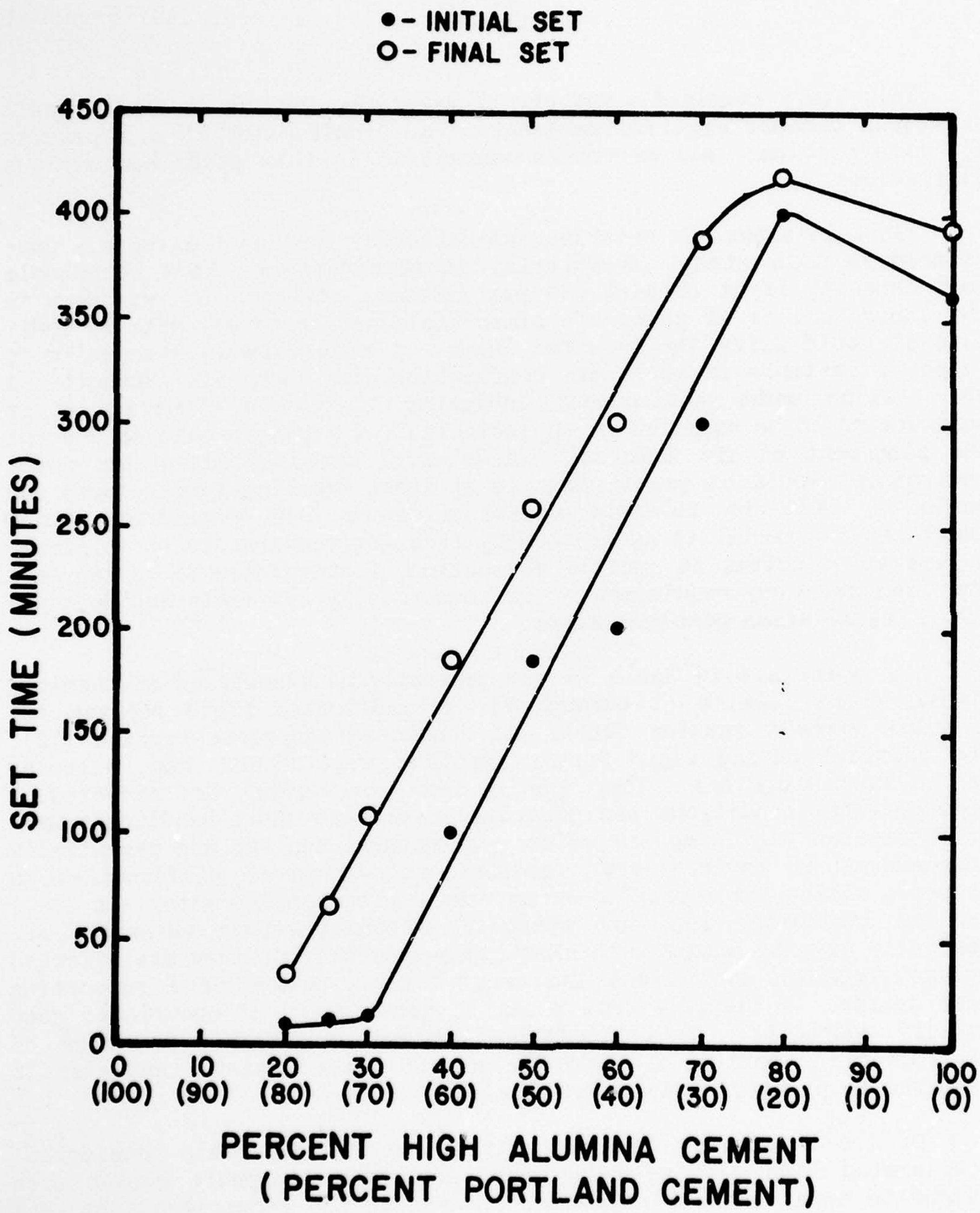


Figure 17. Set Times for Mixtures of Portland and High Alumina Cements

## SECTION X

## CONCLUSION

This study examined a variety of materials for use in rapid repair of weapon damaged airfield pavements. No single material is a panacea for this problem. All materials identified in this study had serious limitations.

Table 14 shows the relative evaluation of the major materials considered in this study. A material is considered to have acceptable load capacity if it obtains 400 psi flexural strength in two hours in the laboratory or if there are other field or laboratory data to indicate it could carry the required loads. A materials load capacity is rated as variable if there are conflicting data about its strength. A poor rating under environment indicates that cold temperatures or moisture could be expected to appreciably slow strength gain or prevent the placement of the material. A material rated as acceptable under environment would be usable down to at least freezing temperatures and would be able to tolerate excess moisture. An excellent rating indicates a material is unaffected by freezing temperature or moisture. A material receives an overall evaluation of acceptable if it can meet the load carrying requirements, is commercially available and no major field installation problem exists.

The materials in Table 14 may generally be classified as chemical curing rigid repairs (1 through 7), prefabricated rigid repairs (8) flexible asphalt repairs (9-11) and compacted aggregate repairs (12). The chemical curing rigid repairs provide a structural cap, allowing use of weak subgrades. They require time for curing, are affected by environmental conditions and generally have very short handling times. Prefabricated rigid repairs offer a structural cap and are essentially independent of environmental restrictions. However, difficulties in properly sizing the repair to accept these preassembled materials are a serious limitation for this approach. Asphalt repair materials are generally easy to handle with existing equipment, but they are affected by environmental conditions and require construction of a supporting base course. A flexible repair can be constructed of unsurfaced good quality aggregate. This approach is usable under a wide range of environmental conditions. However, an FOD hazard exists, and time is required to properly compact material.

Of the seven chemical curing rigid repair materials considered, accelerated high alumina cement and magnesium phosphate cement were judged to have the best potential of meeting the requirements of this study. Their major limitations are poor environmental tolerance, additional mixing equipment that must be purchased by the Air Force and short handling times. The portland cement accelerated with sodium

TABLE 14. REPAIR MATERIAL EVALUATION

| Material | Load Capacity | Environment | Estimated Cost ($/CY) | Remarks | Evaluation |
|---|---|---|---|---|---|
| 1. Accelerated Portland Cement | Variable | Poor | $38 | Exact Proportioning Required | Unacceptable |
| 2. Reg Set | Variable | Poor | — | Limited availability | Unacceptable |
| 3. Accelerated High Alumina Cement | Acceptable | Poor | $160 | — | Acceptable |
| 4. VHE | Unknown | Unknown | — | Limited Availability | Unacceptable |
| 5. Fast Fix | Acceptable | Poor | — | Poor Past Performance | Unacceptable |
| 6. Magnesium Phosphate Cement | Acceptable | Poor | $378 - 945 | Republic Steel product gave best results | Acceptable |
| 7. Polymers | Variable | Poor | Variable | More R&D required | Unacceptable |
| 8. Prefabricated (Mat or slabs) | Acceptable | Excellent | ( $10/SF) mat | Field installation problem | Unacceptable |
| 9. Hot Mix Asphalt | Acceptable | Poor | $40 | Heating difficult | Unacceptable |
| 10. Cold Mix | Unacceptable | Poor | $30 | — | Unacceptable |
| 11. Commercial Asphalts | Acceptable | Poor | $35 - 650 | — | Acceptable |
| 12. Compacted Aggregate | Acceptable | Acceptable | $36 | FOD Hazard | Acceptable |

metasilicate was judged unacceptable because of the precise proportioning of the accelerator required. Reg-Set cement and VHE are not readily available at the present time. Fast-Fix cement was judged unacceptable because of poor performance in past Air Force work. The polymers offer some potential, but more work is required to determine their performance capabilities, environmental tolerance and to develop mixing and placing systems. More work is planned with these materials, but they do not meet the commercially available limitations of this project.

The system of using prefabricated mats or precast slabs placed flush with surrounding pavement must first solve the problem of cutting and preparing a regular shaped hole. Current rates of pavement removal with existing concrete saws and similar equipment are much too slow. If future tests determine that repair systems using landing mat placed on the pavement rather than flush with it are within acceptable roughness limits, the landing mat repair system is by far the most dependable system.

Hot mix asphalt was judged to be unacceptable because of the time and equipment required to heat it. Conventional cold mix asphalts lack the stability required to withstand aircraft traffic. Three commercial asphalt products were judged as acceptable for this study. The laboratory tests of the cold mix were unable to adequately evaluate their performance. Their rating as acceptable is based primarily on the results of testing in Reference 8. Major limitations for the asphalt materials include poor environmental tolerance and time required to provide a compacted supporting base course. Advantages include ease of use and compatability with existing Air Force civil engineering equipment.

Compacted aggregate can carry the required loads, and, if properly graded, is not affected by moisture. Major limitations of this approach are the time required for compaction of the material and the FOD hazard from loose aggregate. The FOD hazard can be kept to a minimum by placing a membrane such as T-17 over the repair, keeping the surface of the repair wet or stabilizing the surface with a cement or light application of an RC or RS asphalt, but this would require some investigation and field testing.

## SECTION XI

## RECOMMENDATIONS

The literature review and laboratory testing performed in this study provide only limited information. Field testing of the identified materials under F-4 traffic loads is required to complete this evaluation. It is recommended the high alumina cement accelerated with lithium carborate, Republic Steel's magnesium phosphate cement, ZOR-X, Future Patch, Amalgapave and unsurfaced compacted aggregate be evaluated in accelerated traffic tests.

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APPENDIX A

AMALGAPAVE TEST RESULTS

| Sample | Percent SC-250 | Percent Diazite | Specific Gravity | Max. Theor. Sp. Gr. | Voids Tot. MlK | % Voids Filled | Unit Weight (Lo/Cu.Ft) | Marshall Stab.(lbs) | Flow (1/100 in) |
|---|---|---|---|---|---|---|---|---|---|
| 1, 2, 3[a] | 5.42 | 1.0 | 2.357 | 2.434 | 3.16 | 79.8 | 147.1 | 812 | 11 |
| 4, 5, 6 | 5.29 | 0.5 | 2.362 | 2.467 | 4.26 | 74.2 | 147.4 | 545 | 9 |
| 7, 8, 9 | 5.24 | 1.0 | 2.348 | 2.440 | 3.77 | 76.1 | 146.5 | 593 | 10 |
| 10, 11, 12 | 5.51 | 1.5 | 2.316 | 2.439 | 5.04 | 71.1 | 144.5 | 635 | 10 |
| 13, 14, 15 | 5.65 | 2.0 | 2.290 | 2.416 | 5.22 | 70.5 | 142.9 | 705 | 11 |
| 16, 17, 18[a] | 5.80 | 2.0 | 2.279 | 2.407 | 5.32 | 70.1 | 142.2 | 753 | 12 |
| 19, 20*, 21 | 5.78 | 0.0 | 2.366 | 2.478 | 4.52 | 75.1 | 147.6 | 537 | 9 |
| 22, 23, 24 | 5.84 | 3.0 | 2.260 | 2.387 | 5.32 | 70.1 | 141.0 | 651 | 12 |
| 25, 26, 27 | 6.02 | 4.0 | 2.224 | 2.362 | 5.84 | 67.9 | 138.8 | 642 | 15 |
| 28, 29, 30 | 5.11 | 1.0 | 2.284 | 2.450 | 6.78 | 62.1 | 142.5 | 591 | 10 |
| 31, 32, 33 | 5.07 | 1.5 | 2.278 | 2.437 | 6.52 | 63.3 | 142.1 | 683 | 10 |
| 34, 35, 36 | 4.87 | 2.0 | 2.274 | 2.432 | 6.50 | 62.1 | 141.9 | 734 | 12 |
| 37, 38, 39 | 4.89 | 2.5 | 2.247 | 2.405 | 6.57 | 61.4 | 140.2 | 718 | 12 |
| 40, 41, 42 | 5.33 | 3.0 | 2.244 | 2.410 | 6.89 | 62.1 | 140.0 | 793 | 13 |
| 43, 44, 45 | 4.03 | 2.5 | 2.209 | 2.469 | 10.53 | 44.5 | 137.8 | 570 | 12 |
| 46, 47, 48 | 4.57 | 2.5 | 2.231 | 2.430 | 8.19 | 54.2 | 139.2 | 583 | 13 |
| 49, 50, 51 | 5.29 | 2.5 | 2.249 | 2.409 | 6.64 | 63.0 | 140.3 | 582 | 11 |
| 52, 53, 54 | 5.43 | 2.5 | 2.285 | 2.395 | 4.59 | 72.0 | 142.6 | 617 | 12 |
| 55, 56, 57 | 6.35 | 2.5 | 2.293 | 2.378 | 3.57 | 76.6 | 143.1 | 546 | 12 |

[a]Samples compacted at 140°F

| Sample | Percent SC-250 | Percent Diazite | Specific Gravity | Max. Theor. Sp. Gr. | Voids Tot. MlK | % Voids Filled | Unit Weight (Lo/Cu.Ft) | Marshall Stab.(lbs) | Flow (1/100 in) |
|---|---|---|---|---|---|---|---|---|---|
| 58, 59, 60 | 5.64 | 2.5 | 2.244 | 2.394 | 6.27 | 65.8 | 140.0 | 468 | 12 |
| 61, 62, 63[a] | 5.50 | 2.5 | 2.258 | 2.386 | 5.36 | 68.8 | 140.9 | 519 | 9 |
| 64, 65, 66[b] | 5.54 | 2.5 | 2.296 | 2.391 | 3.97 | 75.4 | 143.3 | 769 | 12 |
| 67, 68, 69[c] | 5.62 | 2.5 | 2.308 | 2.393 | 3.55 | 77.8 | 144.0 | 807 | 14 |
| 70, 71, 72[d] | 5.68 | 2.5 | 2.257 | 2.393 | 5.68 | 68.3 | 140.8 | 489 | 12 |
| 73, 74, 75[e] | 5.48 | 2.5 | 2.286 | 2.394 | 4.51 | 72.6 | 142.6 | 640 | 12 |
| 76, 77, 78[f] | 6.03 | 2.5 | 2.313 | 2.380 | 2.82 | 82.6 | 144.3 | 747 | 12 |
| 4.0 A,B,C | 5.14 | 0 | 2.172 | 2.206 | 1.54 | | 135.5 | 526 | 8 |
| 4.5 A,B,C | 5.45 | 0 | 2.275 | 2.487 | 8.52 | | 142.0 | 500 | 9 |
| 5.0 A,B,C | 5.98 | 0 | 2.301 | 2.181 | | | 143.6 | 526 | 9 |
| 5.5 A,B,C | 6.36 | 0 | 2.311 | 2.222 | | | 144.2 | 486 | 10 |
| 6.0 A,B,C | 6.95 | 0 | 2.361 | 2.131 | | | 147.3 | 503 | 10 |
| 6.5 A,B,C | 7.13 | 0 | 2.347 | 2.175 | | | 146.5 | 545 | 11 |

[a] Compaction pressure 150 psi
[b] Compaction pressure 250 psi
[c] Compaction pressure 300 psi
[d] Compaction effort 20 revolutions
[e] Compaction effort 40 revolutions
[f] Compaction effort 60 revolutions

| Sample | Percent* Bitumen | Percent Diazite | Specific Gravity | Marshall Stability (lbs) | Flow (1/100 in) |
|---|---|---|---|---|---|
| 1 | | 1.0 | 2.357 | 810 | 11 |
| 2 | | 1.0 | 2.357 | 854 | 11 |
| 3 | | 1.0 | 2.356 | 771 | 11.5 |
| Average | 6.36 | | 2.357 | 812 | 11 |
| 4 | | 0.5 | 2.372 | 651 | 9 |
| 5 | | 0.5 | 2.369 | 476 | 10 |
| 6 | | 0.5 | 2.345 | 508 | 7 |
| Average | 6.36 | | 2.362 | 545 | 9 |
| 7 | | 1.0 | 2.357 | 518 | 10 |
| 8 | | 1.0 | 2.339 | 571 | 11 |
| 9 | | 1.0 | 2.347 | 691 | 10 |
| Average | 6.18 | | 2.348 | 593 | 10 |
| 10 | | 1.5 | 2.302 | 543 | 10 |
| 11 | | 1.5 | 2.352 | 761 | 10 |
| 12 | | 1.5 | 2.294 | 600 | 10 |
| Average | 6.91 | | 2.316 | 635 | 10 |
| 13 | | 2.0 | 2.300 | 702 | 11 |
| 14 | | 2.0 | 2.293 | 712 | 11 |
| 15 | | 2.0 | 2.289 | 702 | 11 |
| Average | 7.50 | | 2.290 | 705 | 11 |
| 16 | | 2.0 | 2.279 | 722 | 13 |
| 17 | | 2.0 | 2.281 | 776 | 13 |
| 18 | | 2.0 | 2.276 | 761 | 11 |
| Average | 7.65 | | 2.279 | 753 | 12 |
| 19 | | 0 | 2.358 | 454 | 9 |
| 20 | | 0 | 2.370 | 543 | 9 |
| 21 | | 0 | 2.371 | 614 | 10 |
| Average | 5.78 | | 2.366 | 537 | 9 |

*Includes Diazite and SC-250

| Sample | Percent Bitumen | Percent Diazite | Specific Gravity | Marshall Stability (lbs) | Flow (1/100 in) |
|---|---|---|---|---|---|
| 22 | | 3.0 | 2.268 | 692 | 12 |
| 23 | | 3.0 | 2.255 | 620 | 12 |
| 24 | | 3.0 | 2.257 | 641 | 13 |
| Average | 5.84 | | 2.260 | 651 | 12 |
| 25 | | 4.0 | 2.252 | 720 | 19 |
| 26 | | 4.0 | 2.217 | 590 | 13 |
| 27 | | 4.0 | 2.202 | 615 | 14 |
| Average | 6.02 | | 2.224 | 642 | 15 |
| 28 | | 1.0 | 2.278 | 610 | 10 |
| 29 | | 1.0 | 2.297 | 625 | 10 |
| 30 | | 1.0 | 2.278 | 537 | 10 |
| Average | 5.11 | | 2.284 | 591 | 10 |
| 31 | | 1.5 | 2.268 | 595 | 10 |
| 32 | | 1.5 | 2.277 | 761 | 10 |
| 33 | | 1.5 | 2.290 | 692 | 11 |
| Average | 5.07 | | 2.278 | 683 | 10 |
| 34 | | 2.0 | 2.266 | 781 | 11 |
| 35 | | 2.0 | 2.276 | 681 | 12 |
| 36 | | 2.0 | 2.279 | 742 | 12 |
| Average | 4.87 | | 2.274 | 734 | 12 |
| 37 | | 2.5 | 2.261 | 791 | 12 |
| 38 | | 2.5 | 2.234 | 632 | 13 |
| 39 | | 2.5 | 2.246 | 731 | 12 |
| Average | 4.89 | | 2.247 | 718 | 12 |
| 40 | | 3.0 | 2.237 | 742 | 14 |
| 41 | | 3.0 | 2.253 | 857 | 12 |
| 42 | | 3.0 | 2.241 | 781 | 13 |
| Average | 5.33 | | 2.244 | 793 | 13 |

| Sample | Percent SC-250 | Percent Diazite | Specific Gravity | Marshall Stability (lbs) | Flow (1/100 in) |
|---|---|---|---|---|---|
| 43 | | 4.0 | 2.210 | 586 | 12 |
| 44 | | 4.0 | 2.213 | 586 | 12 |
| 45 | | 4.0 | 2.205 | 539 | 12 |
| Average | 4.03 | | 2.209 | 570 | 12 |
| 46 | | 4.5 | 2.218 | 559 | 14 |
| 47 | | 4.5 | 2.241 | 559 | 13 |
| 48 | | 4.5 | 2.233 | 631 | 13 |
| Average | 4.57 | | 2.231 | 583 | 13 |
| 49 | | 5.0 | 2.258 | 614 | 11 |
| 50 | | 5.0 | 2.232 | 517 | 11 |
| 51 | | 5.0 | 2.257 | 614 | 12 |
| Average | 5.29 | | 2.249 | 582 | 11 |
| 52 | | 5.5 | 2.284 | 588 | 11 |
| 53 | | 5.5 | 2.290 | 596 | 12 |
| 54 | | 5.5 | 2.282 | 667 | 12 |
| Average | 5.43 | | 2.285 | 617 | 12 |
| 55 | | 6.0 | 2.300 | 556 | 12 |
| 56 | | 6.0 | 2.309 | 489 | 12 |
| 57 | | 6.0 | 2.278 | 591 | 11 |
| Average | 6.35 | | 2.293 | 546 | 12 |
| 58 | | 2.5 | 2.260 | 539 | 12 |
| 59 | | 2.5 | 2.229 | 437 | 12 |
| 60 | | 2.5 | 2.242 | 427 | 11 |
| Average | 5.64 | | 2.244 | 468 | 12 |
| 61 | | 2.5 | 2.247 | 488 | 8 |
| 62 | | 2.5 | 2.255 | 498 | 9 |
| 63 | | 2.5 | 2.272 | 570 | 10 |
| Average | 5.50 | | 2.258 | 519 | 9 |

| Sample | Percent Bitumen | Percent Diazite | Specific Gravity | Marshall Stability (lbs) | Flow (1/100 in) |
|---|---|---|---|---|---|
| 64 | | 2.5 | 2.291 | 742 | 13 |
| 65 | | 2.5 | 2.301 | 846 | 12 |
| 66 | | 2.5 | 2.296 | 720 | 12 |
| Average | 5.54 | | 2.296 | 769 | 12 |
| 67 | | 2.5 | 2.310 | 864 | 14 |
| 68 | | 2.5 | 2.298 | 753 | 14 |
| 69 | | 2.5 | 2.316 | 804 | 13 |
| Average | 5.62 | | 2.308 | 807 | 14 |
| 70 | | 2.5 | 2.253 | 488 | 12 |
| 71 | | 2.5 | 2.259 | 521 | 12 |
| 72 | | 2.5 | 2.260 | 459 | 12 |
| Average | 5.68 | | 2.257 | 489 | 12 |
| 73 | | 2.5 | 2.291 | 698 | 13 |
| 74 | | 2.5 | 2.275 | 598 | 12 |
| 75 | | 2.5 | 2.292 | 624 | 12 |
| Average | 5.48 | | 2.286 | 640 | 12 |
| 76 | | 2.5 | 2.307 | 776 | 13 |
| 77 | | 2.5 | 2.325 | 814 | 12 |
| 78 | | 2.5 | 2.306 | 651 | 12 |
| Average | 6.03 | | 2.313 | 747 | 12 |

| Sample | Percent SC-250, Bitumen | Percent Diazite | Specific Gravity | Marshall Stability (lbs) | Flow (1/100 in) |
|---|---|---|---|---|---|
| 4A | | | 2.201 | 567 | 5 |
| 4B | | | 2.261 | 520 | 8 |
| 4C | | | 2.054 | 492 | 10 |
| Average | 5.14 | 0 | 2.172 | 526 | 8 |
| 4.5A | | | 2.275 | 576 | 9 |
| 4.5B | | | 2.286 | 406 | 10 |
| 4.5C | | | 2.263 | 517 | 9 |
| Average | 5.45 | 0 | 2.275 | 500 | 9 |
| 5A | | | 2.307 | 519 | 9 |
| 5B | | | 2.286 | 510 | 10 |
| 5C | | | 2.310 | 549 | 9 |
| Average | 5.98 | 0 | 2.301 | 526 | 9 |
| 5.5A | | | 2.294 | 410 | 10 |
| 5.5B | | | 2.306 | 437 | 10 |
| 5.5C | | | 2.333 | 610 | 10 |
| Average | 6.36 | 0 | 2.311 | 486 | 10 |
| 6A | | | 2.342 | 450 | 10 |
| 6B | | | 2.358 | 468 | 10 |
| 6C | | | 2.383 | 590 | 11 |
| Average | 6.95 | 0 | 2.361 | 503 | 10 |
| 6.5A | | | 2.353 | 570 | 11 |
| 6.5B | | | 2.347 | 588 | 11 |
| 6.5C | | | 2.340 | 476 | 12 |
| Average | 7.13 | 0 | 2.347 | 545 | 11 |

| Sample | Bitumen (%)[a] | Diazite (%)[b] | SC-250 (%)[c] |
|---|---|---|---|
| 1, 2, 3 | 6.36 | 1.0 | 5.42 |
| 4, 5, 6 | 5.76 | 0.5 | 5.29 |
| 7, 8, 9 | 6.18 | 1.0 | 5.24 |
| 10, 11, 12 | 6.91 | 1.5 | 5.51 |
| 13, 14, 15 | 7.50 | 2.0 | 5.65 |
| 16, 17, 18 | 7.65 | 2.0 | 5.80 |
| 19, 20, 21 | 5.78 | 0.0 | 5.78 |
| 22, 23, 24 | 8.58 | 3.0 | 5.84 |
| 25, 26, 27 | 9.63 | 4.0 | 6.02 |
| 28, 29, 30 | 6.05 | 1.0 | 5.11 |
| 31, 32, 33 | 6.47 | 1.5 | 5.07 |
| 34, 35, 36 | 6.74 | 2.0 | 4.87 |
| 37, 38, 39 | 7.21 | 2.5 | 4.89 |
| 40, 41, 42 | 8.09 | 3.0 | 5.33 |
| 43, 44, 45 | 6.37 | 2.5 | 4.03 |
| 46, 47, 48 | 6.90 | 2.5 | 4.57 |
| 49, 50, 51 | 7.60 | 2.5 | 5.29 |
| 52, 53, 54 | 7.74 | 2.5 | 5.43 |
| 55, 56, 57 | 8.63 | 2.5 | 6.35 |
| 58, 59, 60 | 7.94 | 2.5 | 5.64 |
| 61, 62, 63 | 7.80 | 2.5 | 5.50 |
| 64, 65, 66 | 7.84 | 2.5 | 5.54 |
| 67, 68, 69 | 7.92 | 2.5 | 5.62 |
| 70, 71, 72 | 7.98 | 2.5 | 5.68 |
| 73, 74, 75 | 7.79 | 2.5 | 5.48 |
| 76, 77, 78 | 8.32 | 2.5 | 6.03 |

[a] Bitumen content of sample in the laboratory as a percent of sample weight.

[b] Percent of aggregate weight.

[c] Calculated content of SC-250 obtained by subtracting weight of diazite added to the sample from weight of bitumen extracted in the laboratory. Results given as a percent of sample weight.

# APPENDIX B
## ACCELERATED HIGH ALUMINA CEMENT TEST RESULTS

| | Acc | Ret | W/C | Cure | Cure Time | Flexural Strength | Performer | Remarks |
|---|---|---|---|---|---|---|---|---|
| 1. | .06 | .03 | .4 | Air/p | 2:00 | 167 | CERF | Five minutes working time. Cure: Air cure, covered with plastic. |
| 2. | .06 | .03 | .24 | Air/p | 2:00 | - | CERF | Too dry to test. |
| 3. | .06 | .03 | .30 | Air/p | 2:00 | - | CERF | Too dry to test. |
| 4. | .06 | .03 | .30 | MR | 1:47 | 498<br>480 | CERF | Cure: Moisture Room (MR) |
| 5. | .06 | .06 | .34 | MR | 1:45 | 350<br>377 | CERF | - |
| 6. | .06 | .06 | .37 | MR | 1:52 | 457<br>443 | CERF | - |
| 7. | .06 | .06 | .40 | MR | 1:55 | 510<br>533 | CERF | - |
| 8. | .03 | .12 | .40 | MR | >8:00 | - | CERF | - |
| 9. | .03 | 0 | .40 | MR | 0:30 | 0 | CERF | - |
| 10. | .03 | 0 | .40 | MR | 1:00 | 167 | CERF | - |
| 11. | .03 | 0 | .40 | MR | 1:30 | 393 | CERF | - |
| 12. | .03 | 0 | .40 | MR | 2:00 | 440 | CERF | - |
| 13. | .03 | 0 | .40 | MR | 3:00 | 530 | CERF | - |

## APPENDIX B (Continued)

| | Acc | Ret | W/C | Cure | Time | Fl | Performer | Remarks |
|---|---|---|---|---|---|---|---|---|
| 14. | .03 | .00 | .40 | MR | 4:00 | 493 | CERF | - |
| 15. | .03 | .00 | .40 | MR | 8:00 | 478 | CERF | - |
| 16. | .03 | .00 | .40 | MR | 12:00 | 512 | CERF | - |
| 17. | .03 | .00 | .40 | MR | 24:00 | 503 | CERF | - |
| 18. | .03 | .00 | .40 | Air/p | 2:00 | 410 | CERF | Ambient: 72oF, Sample[a]: 155oF, |
| 19. | .03 | .00 | .40 | Air/p | 2:00 | 148 | CERF | Ambient: 68oF, Sample 100°F, Materials[b]: 58°F. |
| 20. | .03 | .00 | .40 | Air/p | 3:00 | 209 | CERF | Ambient: 68oF, Sample 100oF, Materials 58oF. |
| 21. | .03 | .00 | .40 | Air/p | 24:00 | 438 | CERF | Ambient: 68oF, Sample 100oF, Materials: 58oF. |
| 22. | .03 | .00 | .40 | Air/B + P | 2:00 | 308 | CERF | Cure: wet burlap and plastic. |
| 23. | .03 | .00 | .40 | MR | 2:00 | 72 | CERF | Ambient: 72oF, Sample 155oF |
| 24. | .03 | .00 | .40 | Imm | 2:00 | 78 | CERF | Cure: Immersion in water Ambient: 72oF, Sample |
| 25. | .06 | .00 | .40 | Air/B+P | 1:00 | 202 | CEC | |

[a] Maximum measured temperature of concrete before sample hardened.
[b] Temperature of materials before mixing.

## APPENDIX B (Continued)

| | Acc | Ret | W/C | Cure | Time | Fl | Performer | Remarks |
|---|---|---|---|---|---|---|---|---|
| 26. | .06 | .00 | .40 | Air/B+P | 8:00 | 209<br>258 | CEC | - |
| 27. | .06 | .00 | .40 | Air/B+P | 3:00 | 361<br>314 | CEC | - |
| 28. | .06 | .00 | .40 | Air/B+P | 4:00 | 345<br>402 | CEC | - |
| 29. | .10 | .00 | .40 | Air/B+P | 1:00 | 192<br>197 | CEC | - |
| 30. | .10 | .00 | .40 | Air/B+P | 2:00 | 333<br>317 | CEC | - |
| 31. | .10 | .00 | .40 | Air/B+P | 3:00 | 340<br>323 | CEC | - |
| 32. | .10 | .00 | .40 | Air/B+P | 4:00 | 381<br>300 | CEC | - |
| 33. | .00 | .00 | .40 | Air/B+P | 24:00 | 445<br>450 | CEC | - |
| 34. | .00 | .00 | .40 | MR | 5:00 | 13 | CERF | 80:20 Portland; high alumina |
| 35. | .00 | .00 | .40 | MR | 5:30 | 15 | CERF | 80:20 Portland: high alumina |
| 36. | .00 | .00 | .40 | MR | 6:00 | 6 | CERF | 80:20 Portland: high alumina |
| 37. | .00 | .00 | .40 | MR | 6:30 | 7 | CERF | 80:20 Portland: high alumina |
| 38. | .00 | .00 | .40 | MR | 7:00 | 9 | CERF | 80:20 Portland: high alumina |
| 39. | .00 | .00 | .40 | MR | 7:30 | 11 | CERF | 80:20 Portland: high alumina |

APPENDIX B (Continued)

| | Acc | Ret | W/C | Cure | Time | Fl | Performer | Remarks |
|---|---|---|---|---|---|---|---|---|
| 40. | .00 | .00 | .40 | MR | 9:00 | 12 | CERF | 80:20 Portland: high alumina |
| 41. | .00 | .00 | .40 | MR | 24:00 | 143<br>149 | CERF | 80:20 Portland: high alumina |
| 42. | .00 | .00 | .40 | MR | 72:00 | 436<br>441<br>433 | CERF | 80:20 Portland: high alumina |
| 43. | .00 | .00 | .40 | MR | 168:00 | 545 | CERF | 80:20 Portland: high alumina |
| 44. | .06 | .06 | .40 | -- | --- | -- | CERF | Poor penetration in Uniform Aggregate |
| 45. | .03 | .12 | .40 | MR | 2:00 | 200<br>180 | CERF | $1\frac{1}{2}$ inch uniform Aggregate |
| 46. | .03 | .12 | .40 | MR | 2:00 | 240 | CERF | 1 inch Uniform Aggregate |
| 47. | .00 | .00 | .40 | MR | 4:00 | 65 | CERF | - |
| 48. | .00 | .00 | .40 | MR | 72:00 | 989 | CERF | - |
| 49. | .00 | .00 | .40 | MR | 168:00 | 921 | CERF | - |

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